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QUARTZ CRYSTAL IN BRAZIL

BY W. D. JOHNSTON, JR., AND ROBERT D. BUTLER

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ABSTRACT

The peak production of Brazilian quartz crystal was reached in 1943 when 2411 metric tons were exported. Minas Gerais, Goiaz, and Bahia are the principal producing states. Minor quantities are obtained from Espirito Santo and Northeastern Brazil.

Primary veins and pegmatites yield secondary deposits of eluvial, colluvial, and alluvial origin. The veins range in form from tabular or lenticular bodies, pipes, and pockets to composite lodes and bedded masses. The mineralogy is simple; accessory minerals are few and rare. A small proportion of clear crystals, occurring in vein masses of milky quartz, furnishes the commercial product. Filling, rather than replacement, is believed to be the dominant emplacement process. Pegmatites yield a little commercial quartz. Both residual (eluvial) and water-laid (alluvial) quartz deposits are economically important.

Crystals range up to 40 metric tons in weight; those of 1 to 5 tons occur in many deposits. Quartz from every locality studied is twinned on both the Brazil and Dauphiné laws. Phantoms are abundant.

Field studies reveal little difference between the final quartz from some pegmatites and that from veins. It is inferred that the veins may grade into pegmatites at depth and that both are products of the same mineralogenic epoch. Present evidence does not justify a closer dating for the formation of the veins and pegmatites than the early Paleozoic.

There are few large quartz mines in Brazil. The impressive quartz production during the war years came from many small, scattered workings. Mining methods are primitive, and mechanization was feasible in relatively few areas. The ratio of mine-clean crystal to the total quantity of excavated material varies between 1:1000 and 1:100,000, with an over-all average for the best mines of the order of 1:10,000.

Cost of mining ranges from $2 to $10 a kilogram. The average export value during 1944 was $12.50 per kilogram.

The potential reserves of quartz crystal in Brazil are large, but actual or visual reserves in known districts are small. Future production capacity will be determined by economic factors.

INTRODUCTION

The strategic importance of quartz crystal is discussed in the symposium on quartz oscillator-plates (Frondel and others, 1945). From a minor item, before 1937, Brazil's exports of crystal rose during the war years to her most valuable mineral commodity, when she furnished practically all of the raw quartz from which the oscillator plates used in radio communication by the Armed Services of the United States and Great Britain were cut.

Since 1940, United States government agencies have aided in the production, inspection, and export of Brazilian quartz. The principal agencies concerned in Brazil have been the Metals Reserve Company, the Board of Economic Warfare, and its successors—the Office of Economic Warfare, and the Foreign Economic Administration with its operating branch, the U. S. Commercial Company. During this time, engineers and geologists of these organizations have worked in the crystal areas aiding in problems of reserves and production. An inspection laboratory in Rio de Janeiro has been maintained since 1942, and a branch laboratory in Salvador, Bahia, since mid-1943.

The Brazilian government likewise has been concerned with problems of reserves, production, and grade. Its work has been under the direction of the Departamento Nacional da Produção Mineral and the Coordenação da Mobilização Económica.

This paper, originally planned for the symposium, was not completed in time to be included. Consequently, it has been rewritten to bring the field information up to date and it supplements the paper by Stoiber, Tolman, and Butler (1945) on the geology of quartz-crystal deposits.

ACKNOWLEDGMENTS

This paper, although based primarily upon field observations by the writers, has made use of reports by other engineers and geologists of the Foreign Economic Administration and its preceding organizations who were engaged in the Brazilian quartz program in the years 1942 to 1945. Where use has been made of such reports, the source of the information has been indicated in the text. Otherwise, the observations and interpretations are the responsibility of the authors.

Particular acknowledgment is due H. K. Shearer for the use of Figure 8, to F. D. Hanson for Figures 4 and 14, D. F. Campbell for Figure 13, and to Professor O. H. Leonardos, of the University of Brazil, for Figure 5. Reports by Shearer, Hanson, Campbell, J. F. Bell, D. D. Smythe, T. H. McClelland, F. L. Knouse, and H. C. Alves de Souza have been particularly useful.

The engineers of the F.E.A. have helped in many ways. Particular mention should be made of F. E. Johnson, J. G. Morrison, J. C. Schell, J. I. Duffey, J. W. Malinowsky, and E. A. Escudero.

J. Clarence Wynn, Technician of the U. S. Army Signal Corps Ground Signal Agency, assigned to the Quartz Laboratory in Rio de Janeiro, has been of great help

in sawing and polishing quartz specimens for study and in the drawing of phantoms in quartz crystals.

Many people have generously furnished photographs here reproduced. We are particularly indebted to D. F. Campbell for his pictures of Goiaz. Photographs and drawings without specific acknowledgment of their source are by Johnston.

TABLE 1.—*Brazil's exports of quartz, 1910 to 1945*
(Serviço de Estatística Económica e Financeira, Ministério da Fazenda)

Year	Total weight (kilograms)	Total value (cruzeiros)	Average value per kilogram (cruzeiros)	Year	Total weight (kilograms)	Total value (cruzeiors)	Average value per kilogram (cruzeiros)
1910	24,128	50,123	2.08	1928	308,965	1,325,543	4.29
1911	24,377	59,062	2.42	1929	498,496	1,952,772	3.92
1912	44,981	95,122	2.11	1930	410,591	1,449,759	3.53
1913	43,384	118,161	2.72	1931	537,788	2,259,918	4.20
1914	*	*	*	1932	308,524	822,821	2.67
1915	13,595	34,605	2.54	1933	286,371	1,069,474	3.73
1916	20,351	58,877	2.89	1934	291,551	2,150,896	3.95
1917	3,402	19,164	5.63	1913	230,862	998,701	4.32
1918	12,373	50,128	4.05	1936	224,476	1,345,037	5.99
1919	27,169	143,850	5.29	1937	299,785	3,930,657	13.11
1920	39,626	234,616	5.92	1938	746,872	14,981,120	20.06
1921	40,572	212,993	5.25	1939	677,552	19,096,411	28.18
1922	93,013	334,690	3.60	1940	1,103,021	27,862,945	25.26
1923	151,633	595,541	3.93	1941	1,979,588	98,797,145	49.91
1924	202,715	813,970	4.01	1942	1,769,754	234,826,823	132.69
1925	150,152	661,364	4.44	1943	2,411,115	324,720,830	134.68
1926	161,180	916,633	5.69	1944	1,122,034	280,113,624	249.65
1927	269,465	1,342,495	4.98	1945†	348,396	74,587,537	214.09

* No figures available.
† January to June.

Earl Ingerson, of the Geophysical Laboratory of the Carnegie Institution, who has begun a field and laboratory study of Brazilian quartz, critically read this manuscript, and the writers have profited by his viewpoint.

PRODUCTION

The most comprehensive record of Brazilian production is furnished by the annual export statistics of the Serviço de Estatística Económica e Financeira of the Ministério da Fazenda.

Exports in metric tons and the yearly average value per kilogram in cruzeiros are shown in Figure 1. The figure also shows the yearly average exchange value of the cruzeiro (milréis before 1943) in U. S. currency.

Before 1935, the average value of quartz exported was less than 5 cruzeiros per kilogram. In 1936, principally as a consequence of buying by Germany and Japan in preparation for war and later by the United States and Great Britain, the average value began to increase, reaching 49.90 cruzeiros in 1941, 134.65 cruzeiros in 1943, and a peak value of 249.65 cruzeiros in 1944. With the adoption, in 1942, of stricter inspection in Brazil by both private and government purchasing organizations of Great Britain and the United States, in response to the tremendous demand for

piezo-electric material, the quality of the exports rose sharply. Poorer grades and quartz chippings or "lasca", which had been exported before the war for the manufacture of fused silica and small ornaments, remained in Brazil. Thus, the exports since 1941 consisted of material of higher average grade than had been exported in

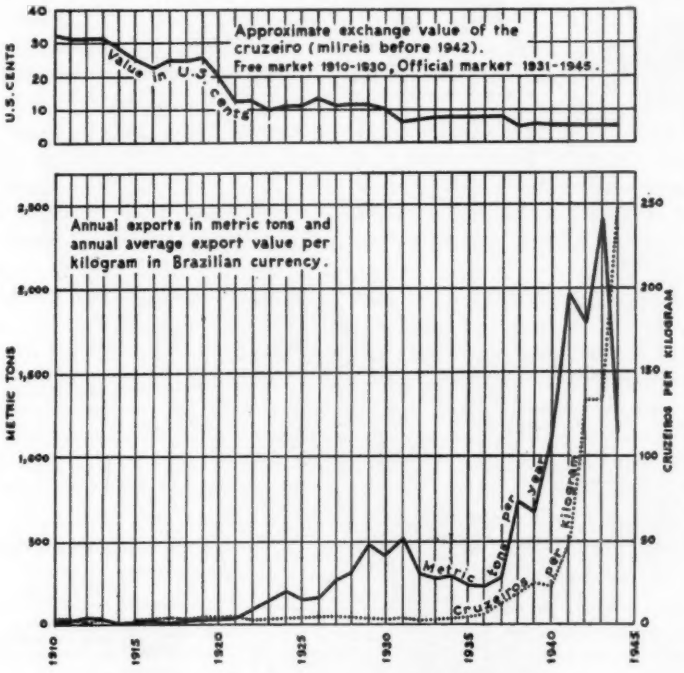

FIGURE 1.—*Brazilian exports of quartz, 1910 to 1944*

Graph shows total yearly tonnage, the average yearly value in cruzeiros per kilogram, and the average yearly exchange rate. From Serviço de Estatística Económica e Financeira, Ministério da Fazenda.

previous years, and the increase in quality is one of the factors that is reflected in the increase in value per kilogram.

Up to the end of 1945, little quartz crystal has been used in Brazil. In 1936, a few experimental oscillators had been made there (Lobo, 1936), and during the war there was a small production of oscillators in São Paulo. In the future, Brazil hopes to fabricate much of her quartz (Alves de Souza, 1944).

GEOGRAPHIC AND GEOLOGIC DISTRIBUTION OF THE DEPOSITS

GENERAL STATEMENT

Minas Gerais, Goiaz, and Bahia, in that order, are the principal producing states: together they have yielded at least 95 per cent of the total Brazilian quartz mined up to present time. Espírito Santo occupies fourth place, and small amounts have come from Ceará, Rio Grande do Norte, Paraíba, and Pará. The general location

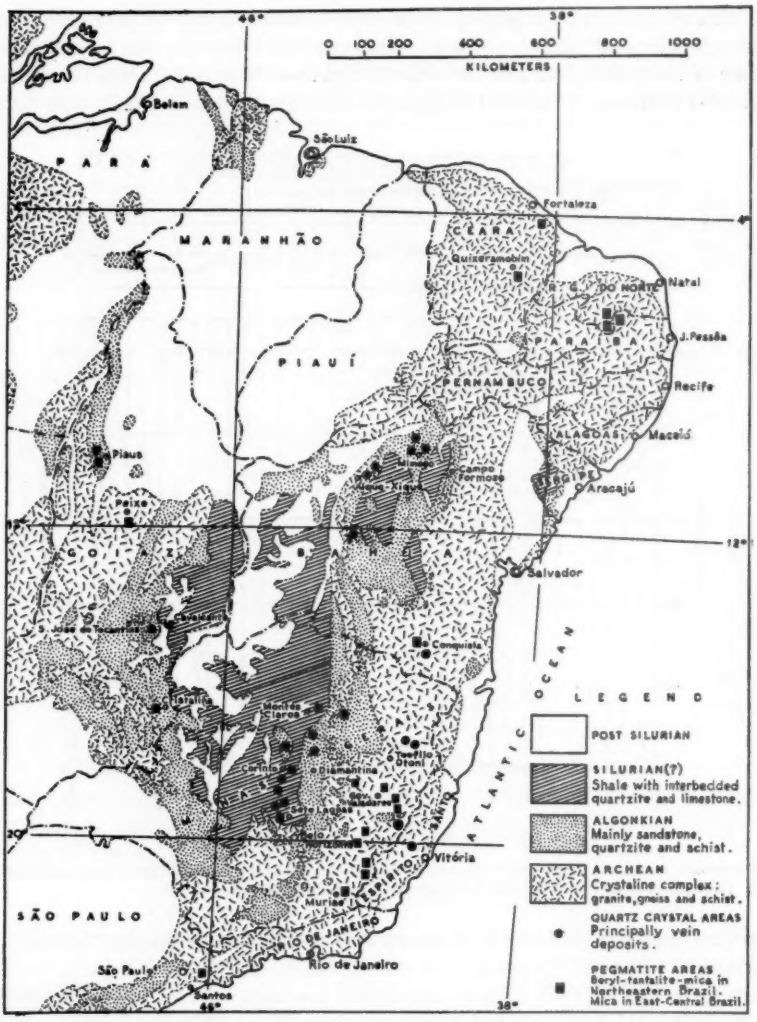

FIGURE 2.—*Geological map showing location of the principal quartz crystal and pegmatite areas*

Based on the geological map of Brazil published by the Departamento Nacional da Produção Mineral in 1942.

of the principal quartz deposits, as well as the pegmatites which have yielded some quartz crystal, is shown on Figure 2.

Most of the important quartz districts are in pre-Cambrian (Algonkian) to Silurian sedimentary rocks. Most of the pegmatites are in pre-Cambrian rocks of the crystalline complex (Archean).

MINAS GERAIS

The principal quartz-producing area of Minas Gerais extends northward from Belo Horizonte, the state capital, to Montes Claros, a distance of approximately 350 kilometers (Fig. 3). The principal towns in this area, which serve in some degree as mining centers, are Sete Lagôas, Curvelo, Corinto, Joaquim Felicio, Diamantina, and Itamarandiba.

Near Sete Lagôas, quartz occurs in veins and composite lodes, and in alluvial deposits derived from them, along a depositional contact where the Bambuí shale (Silurian) rests on granite.

Between Sete Lagôas and Corinto, quartz is found in veins, lodes, and stockworks, with their accompanying secondary deposits, in Bambuí shale.

Northwest of Joaquim Felicio, in the Serra do Cabral, there are numerous veins and stockworks of quartz in Itacolomi (Algonkian) sandstone and quartzites accompanied by eluvial blankets derived through the weathering, in place, of the primary deposits.

On the east side of the crystal-producing area, in the Serra do Cipó and the Serra Mineira and including deposits around Diamantina, Itamarandiba, and Grão Mogol, quartz occurs in veins, pockets, stockworks, and composite lodes in Itacolomi sandstones and quartzites and in eluvial and alluvial deposits derived from them.

With few exceptions, individual deposits are small, and it is the aggregate production of many small deposits that makes the impressive production of Minas Gerais.

North of Teófilo Otoni, in eastern Minas Gerais, quartz is obtained from alluvial gravels that were deposited near the heads of steep valleys cut in Archean schists and gneiss. Most of the quartz is well rounded, but occasional unabraded quartz crystals are found. Tourmaline and beryl (aquamarine) crystals are found in many of the placers. Deeply weathered pegmatites and a few small quartz veins crop out on the hillsides above the alluvial deposits.

East of the Algonkian-Archean contact (Fig. 2), extending from Muriaé to Governador Valadares in the eastern part of Minas Gerais and lying within the crystalline complex (Archean), a series of pegmatite areas yield mica as the principal economic product. A small quantity of quartz crystal is obtained from some of these pegmatites, but the quality is generally poor, and the supply is uncertain.

GOIAZ

The principal quartz-producing areas of Goiaz (Fig. 2) are Cristalina, São José do Tocantins-Cavalcante, and Piaus. All three areas yield important quantities of good crystal.

Cristalina, in the southeastern part of the state near the Minas Gerais boundary, is the oldest district in Goiaz. Quartz occurs in veins and pockets localized on sharp flexures in a pre-Cambrian sandstone, tentatively correlated with the Itacolomi of Minas Gerais. Abundant eluvial and some alluvial deposits derived from the veins and pockets have produced at least half of the quartz mined in that area.

In the São José do Tocantins-Cavalcante area, north of Cristalina, quartz occurs

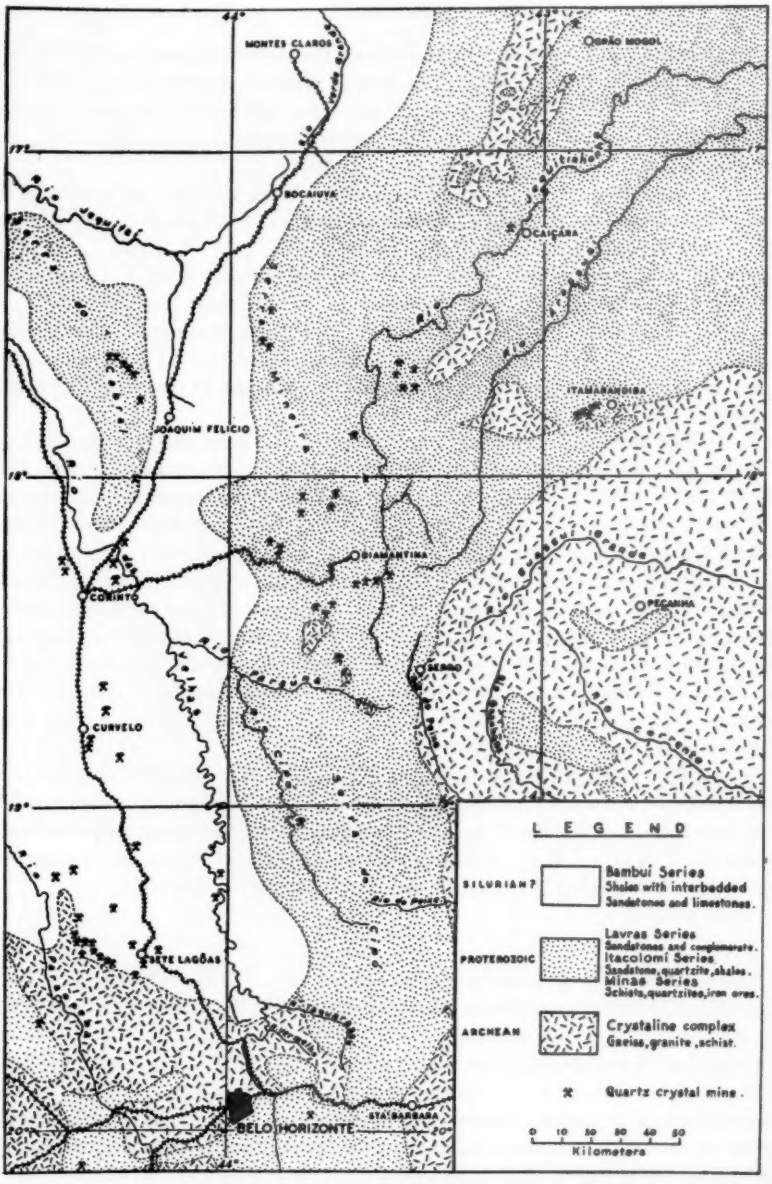

FIGURE 3.—*Map showing location of the principal quartz deposits in Central Minas Gerais*

Based on the geological map by Guimarães and Barbosa published by the Departamento dos Serviços Geográfico e Geológico de Minas Gerais in 1934.

in veins, stockworks, and pockets in sandstone similar to that at Cristalina which has been tentatively correlated with the Itacolomi.

The Piaus area, in the north-central part of the state midway between the Tocantins and Araguaia rivers, was discovered in 1942, and, until airplane service was instituted in 1944, it was the least accessible of the important districts in Brazil. Besides the mines at Piaus, the area includes those at Pium, 6 kms. to the north, the workings at Itaporé, 28 kms. to the south, and the remote and less important Monte Santo workings, 90 kms. to the north. At Pium, Piaus, and Itaporé, the country rock is a mica schist tentatively assigned to the Algonkian (Shearer and Alves de Souza, 1944, map facing p. 34). Large bodies of white to flesh-colored quartz showing strong sheeting and other evidence of movement enclose undeformed bodies of massive quartz and crystals. Some of the crystals are partly clear and yield material of excellent commercial quality.

Quartz has been reported in several localities in Goiaz, north of Piaus, and in the adjacent parts of the neighboring state of Pará; but to the end of 1945 these reported discoveries have not come into appreciable production. The region is unexplored and holds speculative promise for the future.

BAHIA

The two principal quartz-producing regions of Bahia (Fig. 1) have been Mimoso and Xique-Xique, both in the northwestern part of the state. There has been a small production from Conquista, in the south, and from other scattered localities east of the São Francisco River.

The Mimoso area includes the neighboring workings of Alegre, Curral Frio, and Batateiras.

Mimoso lies on the crest of a broad dome which has exposed gently dipping beds of the Caboclo shale (Algonkian?). Quartz occurs in flat concordant veins and in an eluvial blanket from which the first production came.

Alegre, Curral Frio, and Batateiras (Fig. 4) lie in sandstone tentatively correlated with the Lavras series (Cambrian?). At Alegre and Curral Frio, quartz occurs in irregular pipes and, at Batateiras, in flat veins concordant with the bedding and steeply dipping stockworks that cut it at a high angle.

The Xique-Xique (also spelled Chique-Chique) area was an important center of production in 1940 to 1942, but since then it has shown a marked decline. According to Chapin (1943), semirounded to well-rounded quartz occurs in gravels of probable alluvial origin resting on sandstones, quartzites, and limestones. Some eluvial gravels containing unabraded crystals also occur. Primary quartz was seen only in small veins cutting both sandstones and quartzites and limestone.

The Conquista area, in southern Bahia, has yielded a small production of quartz. According to Smythe (1943), the quartz occurs in vertical lenticular bodies up to several meters in maximum width. Margins of well-crystallized feldspar up to 10 cms. in width lie along the walls, where the center of the body is occupied by milky quartz containing occasional vugs with some clear crystals.

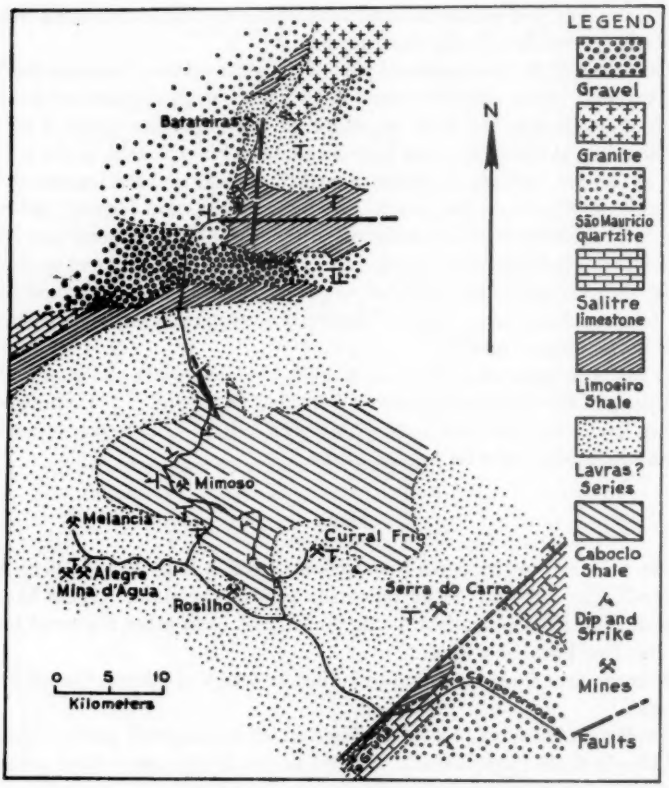

FIGURE 4.—*Sketch map showing the location of mines in the Mimoso area, Bahia*

After F. D. Hanson.

ESPIRITO SANTO

A small but steady supply of quartz has come from the gravels of the small mountain valleys, excavated in gneisses and schists of the Ahrcean complex, in the central part of Espírito Santo. The region is one of the most rugged parts of Brazil, with high relief and steeply graded streams. Both crystal-bearing pegmatites and quartz veins outcrop on the hillsides, but only the gravels, both eluvial and alluvial, have been productive. Knouse (1944) has described these deposits and mapped their distribution.

NORTHEASTERN BRAZIL

The pegmatites of Ceará, Rio Grande do Norte, and Paraíba, which have been worked for tantalite, beryl, cassiterite, spodumene, and amblygonite, have yielded

FIGURE 1. BATATEIRAS, BAHIA
Wall rock is sandstone. Note sandstone inclusion in vein.

FIGURE 2. BATATEIRAS, BAHIA
Wall rock is sandstone.

FIGURE 3. GARÇAS MINE, NEAR CORINTO, MINAS GERAIS
Wall rock is decomposed Bambuí shale.

FIGURE 4. SÃO PEDRO MINE, CRISTALINA, GOIAZ
Wall rock is sandstone. Photo by E. H. Payne.

FIGURE 5. JUIZ MINE, FAZENDA CAPÃO, MINAS GERAIS
Pile of well-formed, but milky, crystals from vugs in sandstone. Photo by E. Escudero.

FIGURE 1. QUARTZ MASS WITHIN PIPE
Note comb structures in pillar between workmen.

FIGURE 2. POCKET OF COMB QUARTZ
In sandstone at edge of pipe.

ALEGRE MINE, BAHIA

a small mount of quartz crystal. It occurs in vugs within the quartz bodies that constitute the final phase of pegmatite differentiation. These deposits have been described by Johnston (1945a; 1945b; 1945c).

TYPES OF DEPOSITS

BASIS FOR GEOLOGIC CLASSIFICATION

Quartz crystal is mined in Brazil from primary deposits, which include both veins and pegmatites, and from secondary deposits that were concentrated by eluvial, colluvial, and alluvial processes. The vein deposits are further classified on the basis of their form. The types here described are:

Primary deposits:
- Veins (veins, composite lodes, pipes and pockets, stockworks, and bedded veins)
- Pegmatites

Secondary deposits:
- Residual blankets (eluvial)
- Hillside creep (colluvial)
- Water-laid (alluvial)

PRIMARY DEPOSITS

Veins.—Primary deposits consisting essentially of quartz without mica, feldspar, or other characteristic pegmatite minerals are here classified as veins. In form, they range from simple tabular bodies, pipes, and pockets to composite lodes. In attitude they range from vertical veins cross-cutting the country rock to flat veins, as at Mimoso in Bahia, that parallel the bedding of the enclosing sediments.

General Features: The veins consist principally of milky comb quartz, usually completely intergrown, and of variable but relatively coarse texture. The general impression is that the milky quartz individuals are 10 cms. or more in length, but in many places crystal outlines cannot be recognized within the mass of the bull quartz. Figure 5 is an excellent example of intergrown quartz at Cristalina, Goiaz,[1] and Plate 1 shows comb structures. Typically, the veins display structure wherein the comb quartz crystals have grown inwards from the walls toward the centers of the veins. Vugs, lined with well-formed crystals, are usually abundant. Occasional crystals in these vugs have clear, transparent prisms or terminations which furnish the material suited for the manufacture of oscillators (Fig. 6). Large clear crystals are relatively rare, whereas small clear prisms are very common.

Vugs range from a few cubic centimeters to several cubic meters across and are filled to varying degrees with crystals, some clear but the majority principally milky. In some places, small vugs are nearly filled with one or two medium-sized crystals, with the remainder of the vug empty or containing secondary oxides and clay. In other cases, small vugs are lined with drusy quartz, clear, but too small to be marketable. In large vugs, the interior may be filled with clay or may be empty, and the crystals which project from the walls toward the center of the vug show a wide range

[1] The reader should clearly realize that this and the following figures showing sketches of comb quartz outcrops are diagrammatic and, in some degree, interpretative.

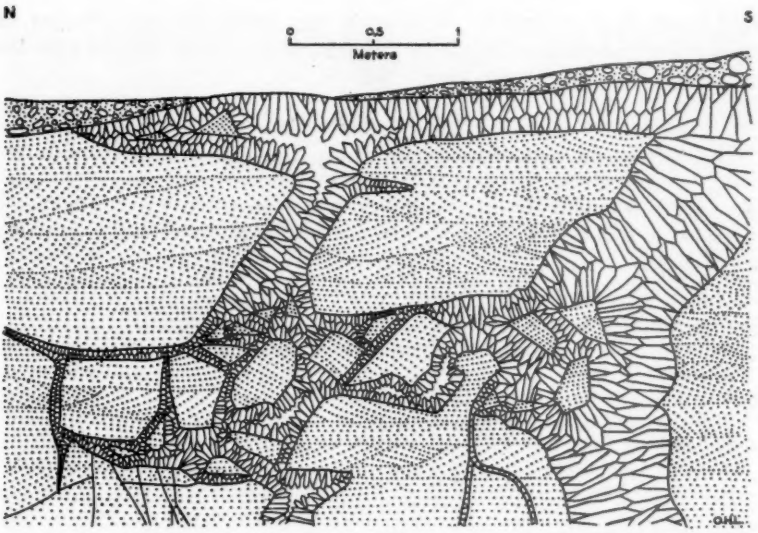

FIGURE 5.—*Sketch of an outcrop of comb quartz at the Roncador mine, Cristalina, Goiaz*

After Othon H. Leonardos.

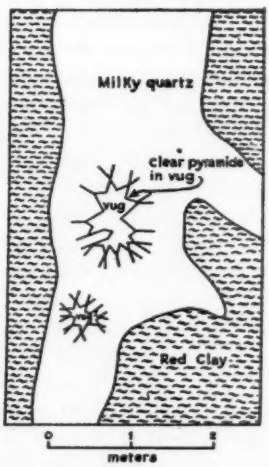

FIGURE 6.—*Sketch of outcrop of comb quartz at the Garças mine, near Corinto, Minas Gerais*

Showing milky quartz vein containing vug lined with comb quartz having clear pyramids. The red clay was derived from the weathering of Bambuí shale.

of sizes, development, and clarity. It is very common in such vugs for the terminations of the individual crystals to be discrete, whereas the prisms coalesce.

Individual quartz crystals range in size from a few millimeters to several meters in length. The Rosilho mine in Bahia contains vugs lined with crystals weighing up to 4 tons each. Crystals weighing from half a ton to a ton are common in many districts. Large crystals are usually a milky gray or milky white and are economically worthless. Two or three of the prism faces and the "r" rhombohedron generally show good development. Occasionally a miner encounters a large crystal with a considerable proportion of clear material, in which case a comparative fortune of several thousand dollars may result.

Wall rock of the veins exercises control on the form of the quartz bodies, but apparently not on the quality. The limestone areas in central Minas Gerais, contiguous to the shale and sandstone regions containing crystal, have no commercial deposits. Inasmuch as the areas are small, however, it is impossible to generalize on the favorability of limestone to quartz-crystal deposits, but it is a fact that vein deposits throughout Brazil are restricted to siliceous rocks, such as sandstone and shale. In the Onça-Pacu area, near Sete Lagôs, Minas Gerais, the veins and lode deposits lie along a depositional contact between granite and shale (Fig. 8); elsewhere in Minas Gerais quartz veins occur either in shale or in sandstone (Fig. 3). At Mimoso, Bahia, quartz occurs in flat veins, lying concordantly in the bedding of the gently dipping, enclosing shales. At Batateiras and Alegre, near Mimoso, Bahia, wall rocks are sandstone. In Goiaz, at Cristalina, veins and pockets occur in sandstones, and at Piaus, Pium, and Itaporé, in paraschists.

Fracture filling appears to have been the principal mode of emplacement of quartz in veins. The crystalline structure of the veins typically displays medium- to coarse-grained quartz which grew inward from the walls, a fact which presumably would require the existence of cavities through which the solutions passed and in which the crystals formed. In a few places, quartz crystals have been observed growing outward from the vein or pocket into the wall rock. Where the wall rock is sandstone or quartzite, included sand grains, perhaps showing bedding structures, are fairly common, and numerous specimens of such material are known. Crystals growing outward into the walls have been observed at various places in Minas Gerais, Goiaz, and Bahia.

If the status of knowledge permits generalization, quartz deposits in shale, sandstone, and quartzite usually show inward-growing structure, indicating cavity filling. Deposits in sandstone or quartzite occasionally show outward-growing structures, indicating that replacement also occurred and was in part responsible for the emplacement of the quartz body. In virtually all observations of the occurrence of crystal in mines, the clear crystal seems to have formed as the latest generation of quartz or at least as the end stage of quartz deposition. Furthermore, in all observed cases, whether the wall rock is shale or sandstone and regardless of the inferred origin of the bull quartz, the clear material was deposited in open spaces along with a greater but varying quantity of milky quartz. These open spaces were principally a result of incomplete filling of fractures, but in some of the sandstone deposits the open spaces could have formed through solution (recrystallization voids).

Vugs, even though lined with milky quartz, may be connected with other vugs

containing clear quartz, so that any vug, in either veins or pegmatites, may serve as a guide to clear crystal. Many vugs or vug zones are filled with clay or iron and manganese oxides. Such secondary minerals commonly serve as guides to good crystal. This indicator is not infallible, but in the course of mining, if crystal is not

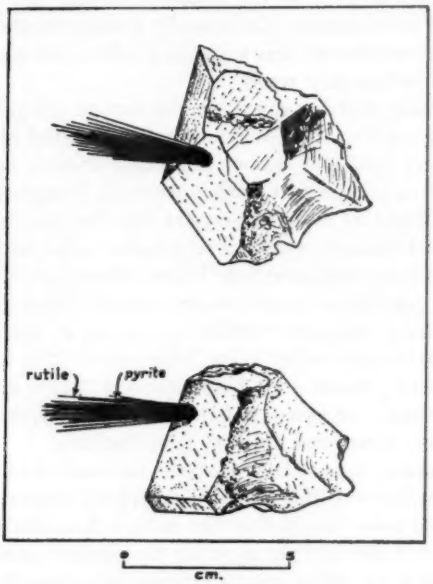

FIGURE 7.—*Sketch of a quartz crystal with rutile and pyrite*

Small pyrite crystals have grown on bundle of rutile needles. Specimen from the collection of E. Ernest S. Brown. Locality unknown.

present in the working face, the best guide to follow is a zone or horizon of vugs, which commonly are conspicuous because of the clay or iron and manganese oxides which thev contain.

In many mines, particularly in the Serra do Cabral of Minas Gerais, vugs contain crystals with phantoms of clay minerals. Numerous observations of crystal aggregates found on the mine dumps suggest that phantoms developed only on the upper surfaces of the crystals. This could be accounted for if fine clay material had been suspended in the quartz-depositing solutions and periodically settled upon the horizontal surface presented and not on the undersides.

Accessory minerals are rare in the vein deposits. Chlorite, sericite, pyrophyllite calcite, manganese and iron oxides, rutile, brookite, and pyrite have been observed. A remarkable specimen (Fig. 7), in the collection of E. Ernest S. Brown, shows bundles of rutile needles to which are attached small pyrite crystals, partially included in the quartz crystal. This specimen shows clearly that the rutile and pyrite crystallized outside the quartz and would have been completely included, as is common in many other specimens, had the quartz crystal continued to grow. Johnston

collected loose rutile fibers in a quartz-lined vug at the Serra da Lagrinha mine, Minas Gerais.

A quartz crystal having a very conspicuous phantom, consisting of clay minerals deposited on the topside of the growing crystal, contains several well-formed rhombohedra of calcite that rest on the phantom plane and are completely included in the quartz crystal. This specimen suggests that the quartz-depositing solutions, at the time the calcite rhombs either fell or grew on the topside surface of the growing quartz crystal, were saturated in calcium carbonate: otherwise the included rhombs would show etching or have lost their distinctive form. The origin of this specimen is not known, but quartz crystals from Sete Lagôas, Minas Gerais, commonly contain calcite inclusions.

Three crystals are known, one from Bahia and two from Minas Gerais, which contain a diamond inclusion. Probably the diamonds were incorporated in the growing crystals and there is no genetic significance.

Yellow quartz reported to have come from Xique-Xique, Bahia, emits an odor of hydrogen sulphide when the surface is abraded. This material was probably derived from a vein deposit; the odor and color presumably are due to liquid inclusions containing hydrogen sulphide and dispersed sulphur.

Quartz crystals from both veins and pegmatites contain liquid inclusions and gas bubbles; some of the inclusions are one or more cubic centimeters in volume. The fluid in many of the inclusions may represent a primary solution. The largest liquid inclusions, some of which are several cubic centimeters in volume, occur in quartz showing skeletal forms resulting from faster growth at intersections of faces than in the center of the faces. From time to time, growth from the corners bridged across the face depressions trapping liquid within the crystal, or adjacent crystals grew together, and the liquid contained in depressions in the joining faces was included within the crystal aggregate. Many crystals of this type have come from the vicinity of Itamarandiba, Minas Gerais.

A late generation of quartz, deposited as a coating on earlier quartz, has been observed in some of the Brazilian deposits. Well-formed amethyst crystals up to 10 cms. in length, attached to large crystals of earlier milky quartz, have been found at Santa Maria, Espírito Santo. At the Onça mine, Sete Lagôas some vugs lined with clear quartz crystals are coated with a drusy layer of fine-grained quartz whose individual crystals are less than a millimeter in diameter.

Several mines are described to give examples of the various types of vein deposits.

Simple Vein Transecting the Bedding of the Country Rock: The Gauche mine (McClelland, 1944b), 68 kms. northwest of Sete Lagôas, is the simplest of the quartz veins that have been studied in detail. The vein is composed of a series of lenses which pinched out horizontally and vertically. In places splits and branches were encountered so that, although the width of the vein itself ranged from a mere stringer to 1½ meters, the mining width attained 5 meters in places due to horses between the splits. The vein strikes N. and shows an average dip of 60° W. Enclosing rocks are shales of the Bambuí series (Silurian), which lie horizontally. The shales are gray green on fresh exposures but weather red or reddish yellow and form a red clay soil at the surface. The vein has been exposed over a length of 730

meters along the strike and has been explored to a maximum depth of 21 meters. The vein material is milky bull quartz, containing a few vugs which are lined or nearly filled with well-formed crystals. The distribution of clear crystal in the vugs, as well as the distribution of the vugs themselves, is very erratic. In the narrower portions of the main vein and in some of the branch veins, comb structures, with quartz crystals projecting inward from the walls, are visible.

A cross-cut, driven from the bottom of a 21-meter shaft in the hanging wall, cut two veins. The smaller averaged 15 centimeters, and the larger 1 meter in width. The yield of 0.355 kilogram of mine-clean crystal per cubic meter of vein material did not permit further exploration of the deposit.

Composite Lodes: The Onça mine (Kerr and Erichsen, 1942; Shearer, 1944), 40 kms. northwest of Sete Lagôas, Minas Gerais, is a composite lode deposit, lying along a shale-granite contact. The lode is exposed in a large open cut for 650 meters along the strike. It has been mined to a maximum depth of 25 meters below the original surface. The lode strikes N. and dips 45°–60° W. Granite is on the east (foot wall) side, and Bambuí shale on the west (hanging wall). In both types of rock, weathering extends to the lowest part of the open cut. The shale is crumpled along the contact, and the dips are steepest immediately next to the granite. Westward from the contact, the degree of crumpling decreases, and the dips decrease.

The lode is composed of veins, stringers, and lenses, disposed irregularly along the contact. In general, cross-cutting stringers are rare, as most of the vein matter lies parallel to the structure of the shales, with all the quartz localized on the shale side of the contact. Narrow veins parallel to the bedding extend into the shale wall. Here and there, small lenses and pods of quartz occur in the shale.

Iron and manganese oxides cement and fill fractures in the quartz-vein matter, and clay is fairly abundant in places. These fillings are a rough guide to crystal because they follow vug structures, and it is there that the commercial crystal occurs.

At Pacú, 3 kilometers north of the Onça mine, the Serrado and Melosinhos mines, of the same general type, lie along the granite-shale contact (Fig. 8).

Shearer concluded that the Bambuí shale was deposited on an irregular granite surface of high relief, and compaction folding and slumping developed the folds and crumples in the shales along the steep granite slopes. Openings that later were filled with quartz were subsequently formed along the contact zone.

Pipes and Pockets: In the São Pedro mine (Trinidade, 1943; Johnston, 1944) at Cristalina, Goiaz, quartz occurs in pipes and pockets in sandstone. The sandstone, which Johnston originally considered to belong to the Bararú formation, he now considers, on lithologic grounds, to be equivalent to one of the pre-Cambrian sandstones of Minas Gerais, possibly the Itacolomí series. At Cristalina, the sandstone lies horizontally except for small local folds. It is conspicuously cross-bedded and contains thin intercalated layers of shale.

The quartz occurs in irregularly shaped pockets (Fig. 9) that range in size from a few centimeters to many meters. The pockets are generally ovoid or lenticular and lie concordantly with the bedding planes. In places the pockets are connected with one another by narrow quartz veins. The pockets of quartz display comb structures with the crystal terminations pointing inward toward the center, indicating that

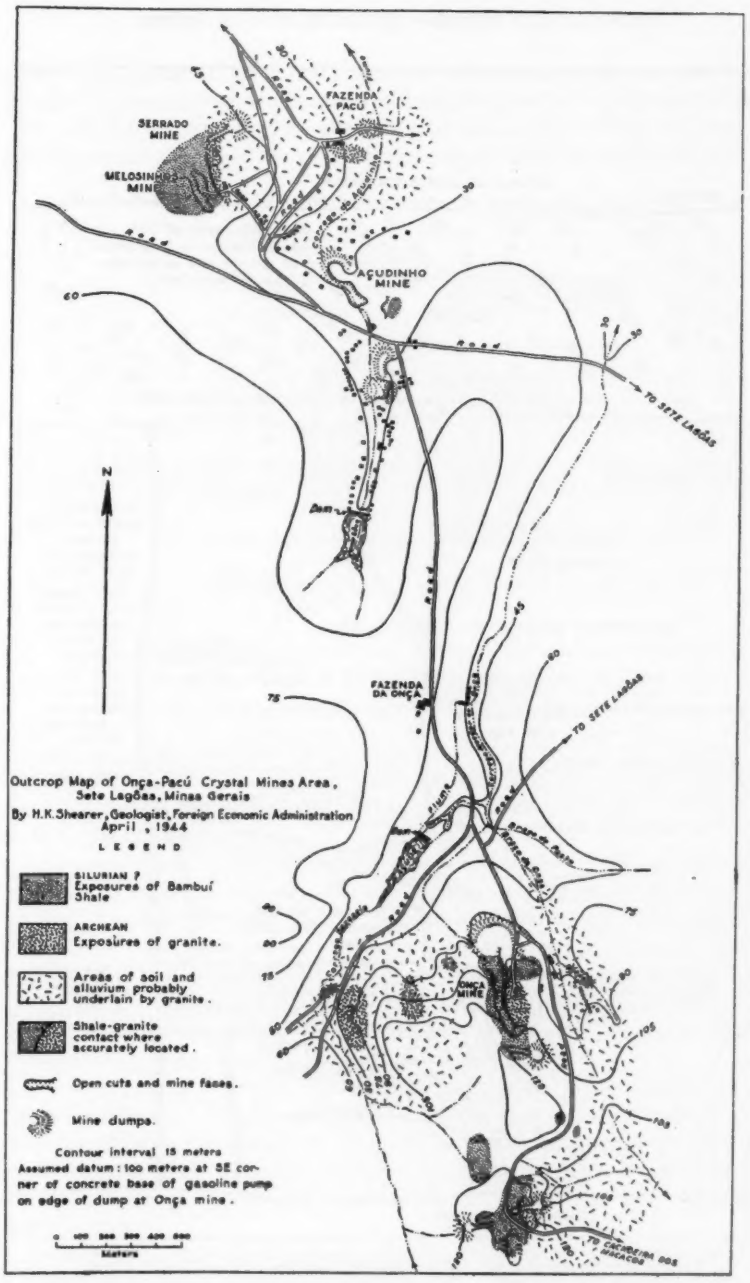
SERRADO MINE
MELOSINHO MINE
FAZENDA PACÚ
AÇUDINHO MINE
TO SETE LAGÕAS
N
Dam
FAZENDA DA ONÇA
TO SETE LAGÕAS
ONÇA MINE
Outcrop Map of Onça-Pacú Crystal Mines Area, Sete Lagôas, Minas Gerais
By H.K. Shearer, Geologist, Foreign Economic Administration
April , 1944
LEGEND
SILURIAN ?
Exposures of Bambuí Shale
ARCHEAN
Exposures of granite.
Areas of soil and alluvium probably underlain by granite.
Shale-granite contact where accurately located.
Open cuts and mine faces.
Mine dumps.
Contour interval 15 meters
Assumed datum: 100 meters at SE corner of concrete base of gasoline pump on edge of dump at Onça mine.
Meters

FIGURE 8.—*Outcrop map of the Onça-Pacú area, Sete Lagôas, Minas Gerais*

After H. K. Shearer.

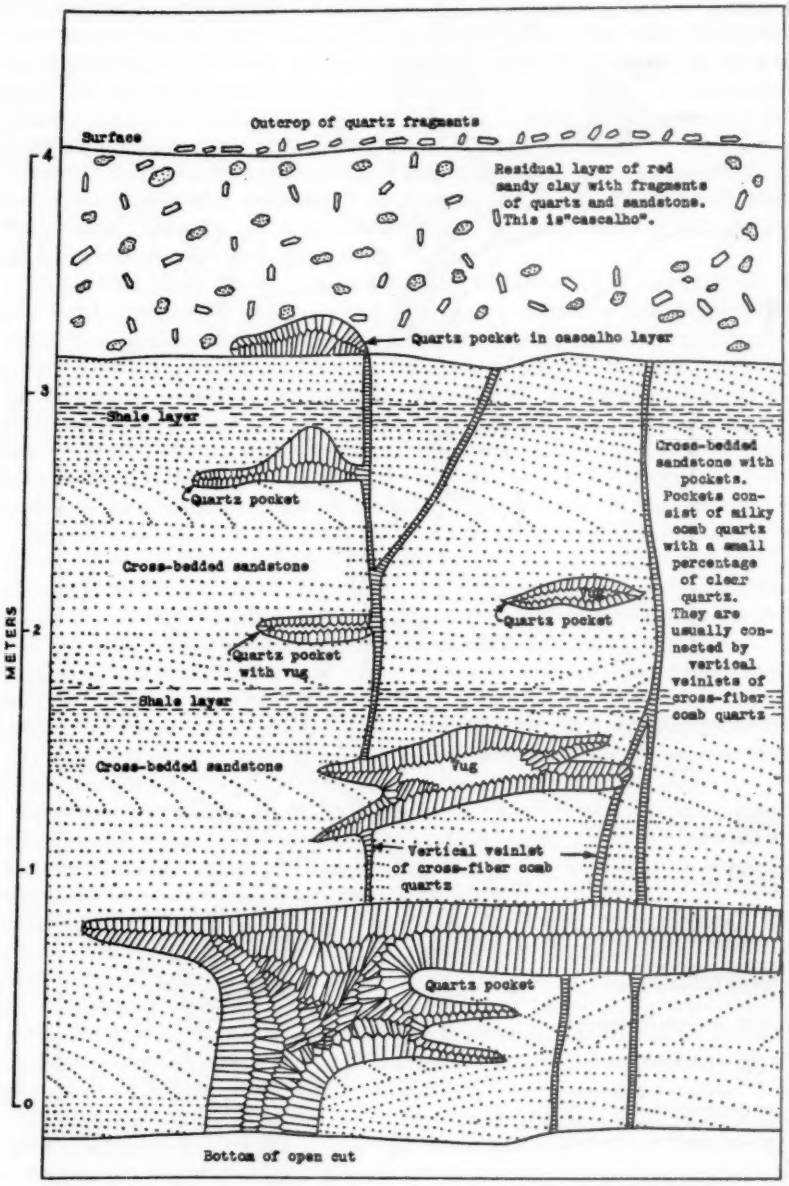
Surface
Outcrop of quartz fragments
Residual layer of red sandy clay with fragments of quartz and sandstone. This is "cascalho".
Quartz pocket in cascalho layer
Shale layer
Quartz pocket
Cross-bedded sandstone
Quartz pocket with vug
Quartz pocket
Shale layer
Cross-bedded sandstone
Vug
Vertical veinlet of cross-fiber comb quartz
Quartz pocket
Bottom of open cut
Cross-bedded sandstone with pockets. Pockets consist of milky comb quartz with a small percentage of clear quartz. They are usually connected by vertical veinlets of cross-fiber comb quartz
METERS
4
3
2
1
0

FIGURE 9.—*Sketch showing pockets, veinlets, and the residual blanket deposit*

Based on exposures in the São Pedro mine, Cristalina, Goiaz.

filling of the pocket occurred (Pl. 1, fig. 4). In some, the entire mass is completely occupied by quartz with terminations of inwardly growing crystal intergrown with those which grow from the opposite side, whereas in others filling was incomplete, and the centers of some of the vugs remain, some of which are filled with white clay.

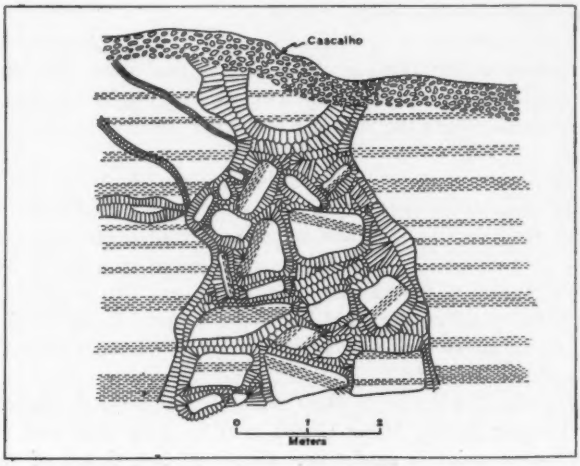

FIGURE 10.—*Sketch at the Morro Rico mine, Cristalina, Goiaz*

Showing jumbled blocks of sandstone cemented by comb quartz. The horizontal plan of this outcrop suggests a collapsed cave rather than a fault.

Some crystals within the vugs have clear terminations and are suitable for commercial purposes, but by far the bulk of the vug fillings is composed of milky, imperfect, bull quartz.

At some mines at Cristalina, notably Morro Rendondo and Morro Rico, pipelike masses of quartz are exposed. Within these lie fragments of sandstone whose random orientation is shown by the interbedded shale layers which they contain (Fig. 10). Fairly coarse-grained comb quartz, grown inwardly, cement the sandstone fragments. The abundance of vugs in these bodies makes it evident that they represent former cavities, probably of solution origin, which were filled by quartz. The pipes themselves were probably solution channels into which the sandstone fragments fell, either before or during quartz filling.

The Alegre mine, 11 kms. southwest of Mimoso, Bahia, is an example of a quartz pipe in sandstone. The country rock is tentatively correlated with the Lavras series (Cambrian). According to Hanson (1944), an inclined pipelike mass of quartz, approximately 10 by 15 meters in horizontal dimensions, was localized by the intersection of two groups of closely spaced joints. It has been mined to a depth of about 20 meters.

The walls of the pipe are extremely irregular; veins, tongues, stringers, and pockets of quartz occur in the surrounding country rock. Most of the quartz in the pipe is milky, bull quartz, but here and there vugs contain well-terminated quartz crystals

(Pl. 2). The vugs are fairly abundant, and in many of them clear, commercial quartz crystals are found. The peripheral quartz bodies, pockets, veins, and stringers show comb structures in which the quartz crystals have grown inward from the walls. Commercial crystals occur within the pipe itself as well as within the peripheral bodies, and the distribution of the vugs is extremely erratic as is the distribution of commercial crystal within the vugs.

Numerous crystals from the Alegre mine contained phantom planes faintly outlined by black manganese oxides. Commonly these phantom planes developed only on the upper portions of the crystals as they were oriented within the vugs, suggesting that manganese oxide, under the influence of gravity, settled on the upper surfaces of the crystals.

Cavity filling was important in the emplacement of the Alegre deposit, as indicated by the inwardly terminating crystals, as well as the evidence of the phantoms. On the other hand, no direct evidence was discerned to controvert the possibility that some or all of the bull quartz, in the pipe itself, formed through the solution and recrystallization, *in situ*, of the quartz of the sandstone. This possible explanation, of course, could be considered for all of the quartz deposits in highly siliceous rocks where there is no direct evidence, such as quartz crystals growing from wall to center, for the pre-existence of cavities.

STOCKWORKS: The Comechas de Meio mine, in the Serra do Cabral, 22 kms. northwest of Joaquim Felicio, Minas Gerais, is an irregular stockwork of comparatively narrow quartz veins in sandstone. Figure 11 is a sketch of the principal working face on November 14, 1944. The veins are filled with comb quartz which has grown inward from the walls toward the center. Although the veins are small, they yield an unusually high percentage of usable quartz in clear terminated prisms. Most of the clear crystals weigh under 200 grams, and few exceed 500 grams. Overlying the stockwork in sandstone is a residual detrital blanket derived from the decomposition, *in situ*, of the quartz-bearing sandstone. This blanket has yielded much good quartz.

The Garças mine, near Corinto, Minas Gerais (Fig. 12; Pl. 3, fig. 2), is a stockwork of quartz veins in red clay drived from the weathering of Bambuí shale. The veins display an irregular pattern and coalesce in places; some are narrow, but many attain widths of a meter or more.

The deposits of the Piaus-Itaporé area in northern Goiaz are large-scale stockworks of quartz veins in deeply weathered mica schist, which Shearer and Alves de Souza (1944, map facing p. 34) have assigned to the Algonkian.

The three principal districts are Piaus, which is 630 kms. airline north of Anápolis, the terminus of the railroad between São Paulo and Goiaz, Pium, 6 kms. north of Piaus, and Itaporé, 24 kms. south of Piaus. The yield of clear quartz from these districts, since the discovery of Pium in 1942, has been high. A fourth district, called Monte Santo, with a small crystal production, is about 90 kms. north of Piaus.

At Pium, Piaus, and Itaporé, the quartz bodies range from a few centimeters to 10 meters or more in width. They cut the schistosity of the enclosing wall rocks at all angles. Most of the quartz is milky to opaque, white to flesh-colored, and shows no external crystal faces. In many places the quartz is strongly sheared, breaking

FIGURE 1. MOSQUITO MINE, NEAR CURVELO, MINAS GERAIS
Four narrow parallel quartz veins cutting Bambuí shale.

FIGURE 2. GARÇAS MINE, NEAR CORINTO, MINAS GERAIS
Stockwork of quartz in weathered Bambuí shale.

VEINS AND STOCKWORKS

FIGURE 1. FOLD IN CABOCLO SHALE
Overlying lower quartz bed.

FIGURE 2. LOWER QUARTZ BED
In Silva Regis mine.

FIGURE 3. CAVITY FROM WHICH VEIN INCLUSION OF CABOCLO SHALE HAS BEEN REMOVED
Shale shows no replacement by quartz.

FIGURE 4. VIEW SHOWING CLOSE SPACING OF PITS AND TYPE OF HOIST USED TO MINE BEDDED VEINS

MIMOSA AREA, BAHIA

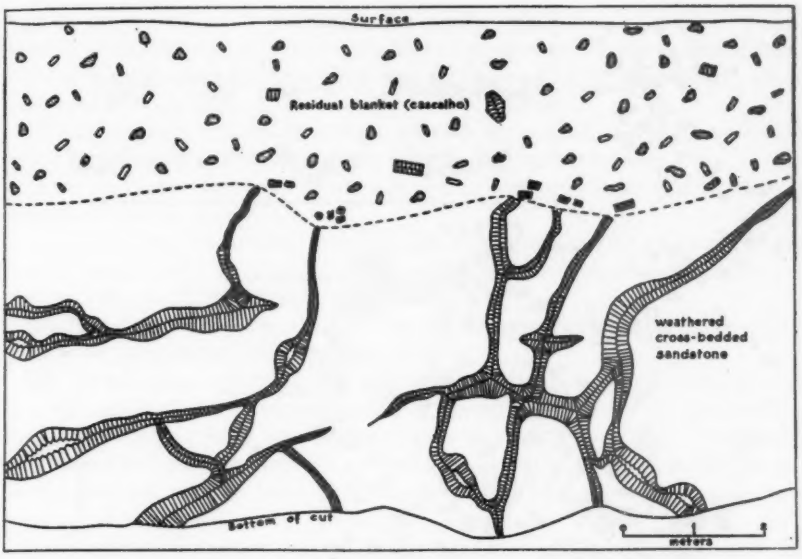

FIGURE 11.—*Sketch at Comechas de Meio mine, Serra do Cabral, Minas Gerais*

Showing stockwork of veinlets filled with comb quartz. The crystals, though small, are of excellent quality.

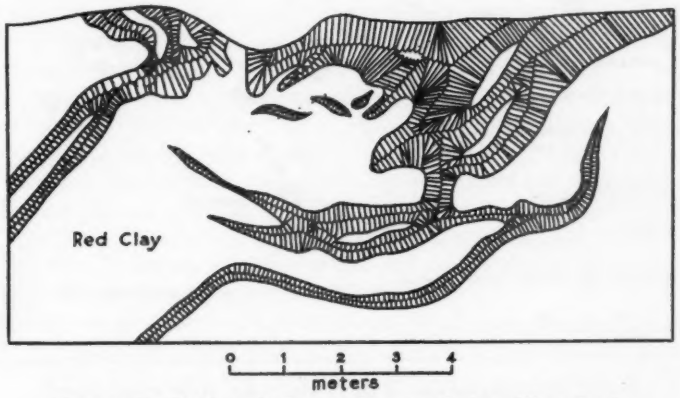

FIGURE 12.—*Sketch at the Garças mine, near Corinto, Minas Gerais*

Showing a stockwork of veins filled with comb quartz. The red clay forming the walls was derived through the weathering of Bambuí shale.

along closely spaced parallel planes. At Itaporé, flesh-colored quartz, with three sets of parting planes at right angles to each other, has a remarkable superficial resemblance to feldspar.

Within the bodies of massive quartz are vugs lined with well-terminated crystals

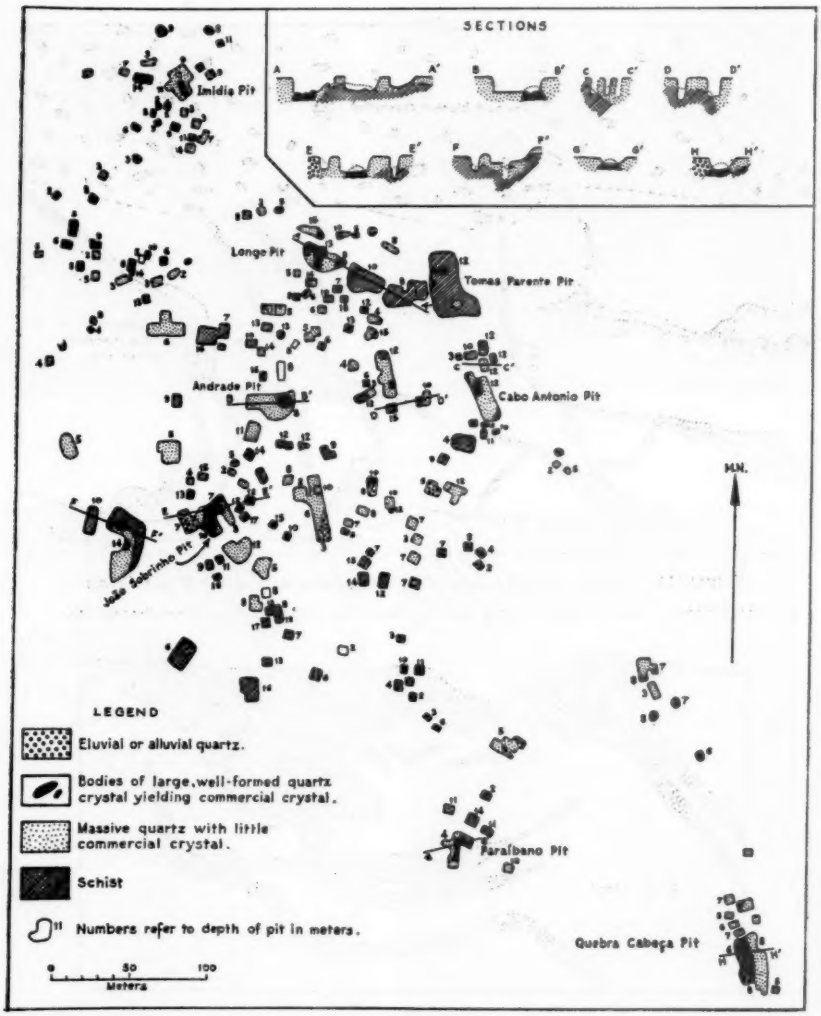

FIGURE 13.—*Geological map of the Itaporé, Goiaz, quartz crystal deposit*

After Donald F. Campbell.

some of which attain gigantic size (Pl. 8). On October 6, 1945, seven well-formed crystals in the Longo pit, at Itaporé (Fig. 13), had rhombohedral faces a meter or more in length. In all three districts, crystals weighing up to 5 tons are abundant, and crystals weighing 25 tons are not rare. The largest crystal observed is estimated to weigh about 40 metric tons.

The large crystals originally were attached to the outer massive quartz, but the

regional movement, which developed the parting planes in the massive quartz, broke most of the large crystals at their bases and developed many cracks in them. Some of these cracks have been filled by a later generation of drusy quartz whose individual crystals are less than a centimeter in diameter.

Some of the large crystals have clear, colorless terminations. These crystals are drilled and blasted into smaller pieces suitable for hand trimming.

There are many unexplored quartz outcrops in Northern Goiaz that which hold promise for future production.

BEDDED VEINS: The Mimoso area (Patury, 1944; Hanson, 1944), about 200 kms. west of Campo Formoso, Bahia, is characterized by quartz veins enclosed concordantly in a flat to slightly dipping shale.

The Mimoso deposits lie on the crest and southern flank of a broad, flat anticlinal dome whose axis plunges gently westward.

The Caboclo shale, which Oliveira and Leonardos (1943, p. 189) consider to be of Cambrian age but which Hanson regards as Algonkian, crops out on the anticlinal crest. The shale is finely laminated and gray to green where fresh. Weathering has changed it to red and red brown and has increased the color contrast between the bedding laminae. A few layers of quartzite ranging from a few centimeters to a meter or more in thickness are interbedded in the shale.

Three horizons or bedded veins of quartz occupy closely spaced positions in the shale. They crop out in the large ravine at the village of Mimoso. Figure 14 taken from Hanson's geological map of Mimoso shows the principal outcrop area of the quartz beds. The upper quartz underlies a known area of about 2½ square kms. on the south flank of the dome. The quartz body ranges in thickness from a few cms. to 2½ meters. The middle quartz bed is thin and of limited extent. The lower quartz bed underlies a known area of about 1½ square kms. It ranges in thickness from a few cms. to a maximum of 4 meters (Pl. 4, fig. 2). The quartz beds are separated by 3 to 5 meters of shale. Vertical or steeply dipping narrow veins (Fig. 15) connect one bed with another.

The principal vein material is massive milky bull quartz containing many vugs, some of which yield clear quartz. Inclusions of shale and of an earlier generation of ribbon quartz are abundant (Fig. 16). The bull quartz displays indistinct comb structures, in many places, which is idealized and exaggerated in the accompanying sketches to indicate the interpreted structures.

The shales contain many small folds, some of which pass into local thrust faults (Fig. 17; Pl. 4, fig. 1). These folds are most marked in the 2 meters immediately above the lower quartz bed and tend to die out upward. As shown in Figure 14, fold axes striking both northeast and northwest occur in the shale overlying both the upper and lower quartz beds. The small folds indicate movement along bedding planes in the shale, and probably the quartz veins occupy bedding-plane faults. Likewise, the ribbon quartz, present as inclusions within the massive bull quartz, preserves a record of interdepositional movements of the vein walls. Shale inclusions in the veins are angular and fresh (Pl. 4, fig. 3).

Johnston believes that these bedded veins were formed by recurrent movement and quartz filling along bedding-plane faults wherein movement resulting in the

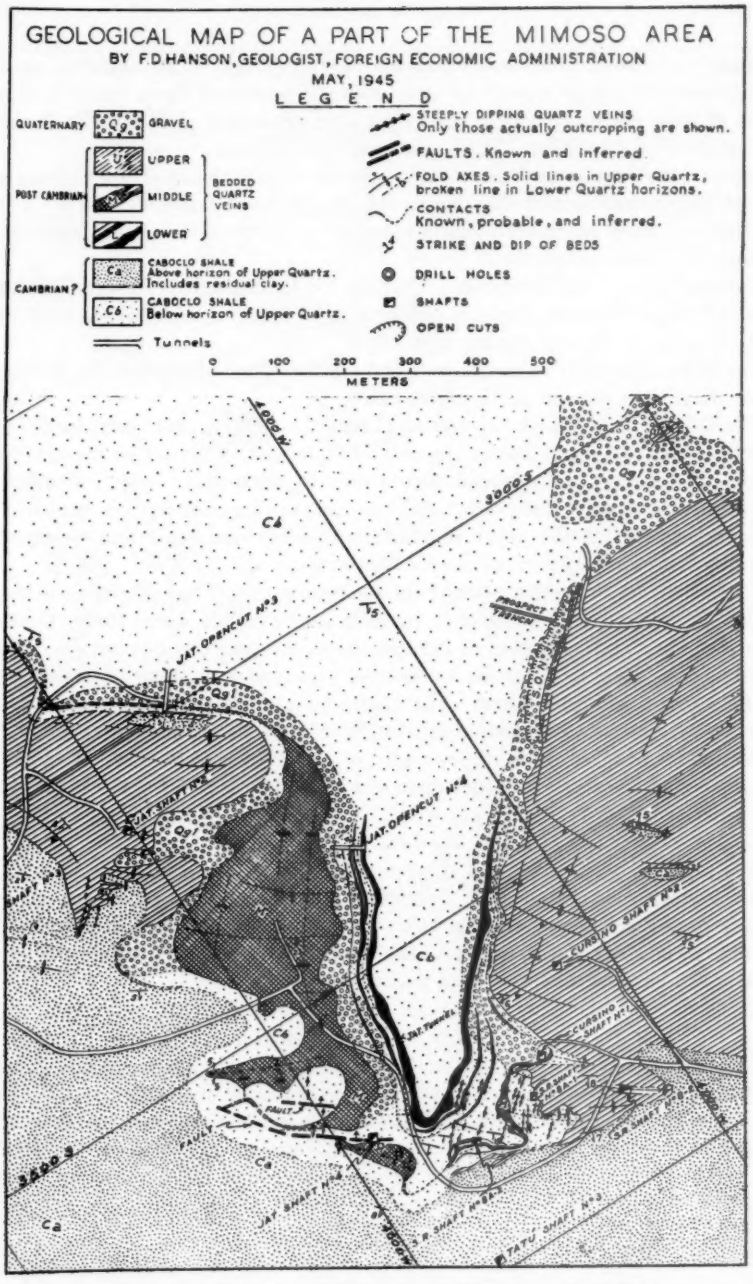

FIGURE 14.—*Geological map of a part of the Mimoso area, Bahia*

After F. D. Hanson.

formation of open spaces alternated with quartz deposition to build up thick but irregular veins. He believes that replacement of the shale by quartz was a very minor process. Hanson, who has done most of the detailed geology in the area,

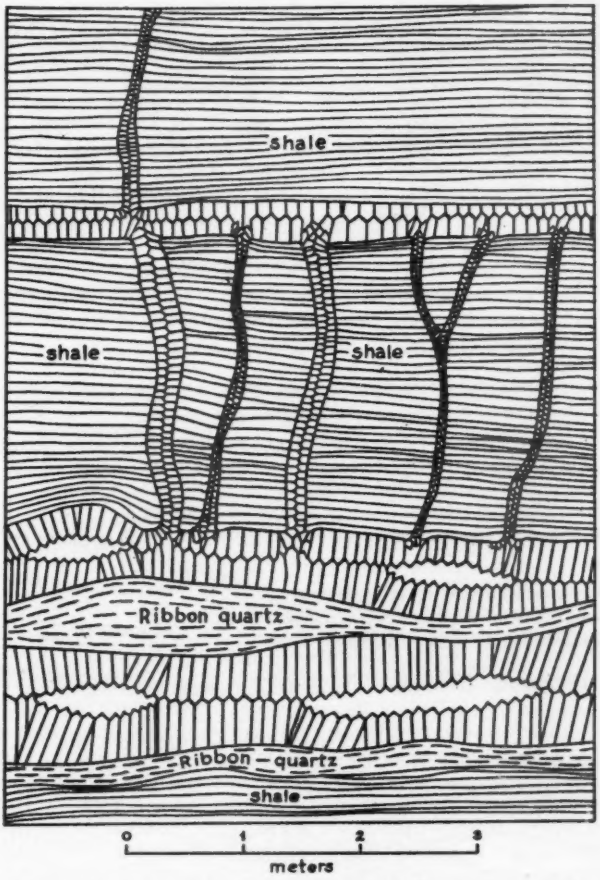

FIGURE 15.—*Sketch of a face in the Silva Regis mine, Mimoso, Bahia*

Showing bedded veins connected by vertical veinlets. The lower quartz bed contains earlier ribbon quartz included in a later generation of comb quartz.

believes, on the other hand, that the bedded veins were formed by replacement of the shale. His evidence will be presented in a separate paper.

At Batateiras, 45 kms. north of Mimoso, Bahia, a series of flat veins, generally concordant with the bedding of the enclosing sandstone of the Lavras Series, crop out for a strike distance of about 800 meters along the face of a steep bluff. The veins and the sandstone beds dip into the hillside at an average angle of 20°. The

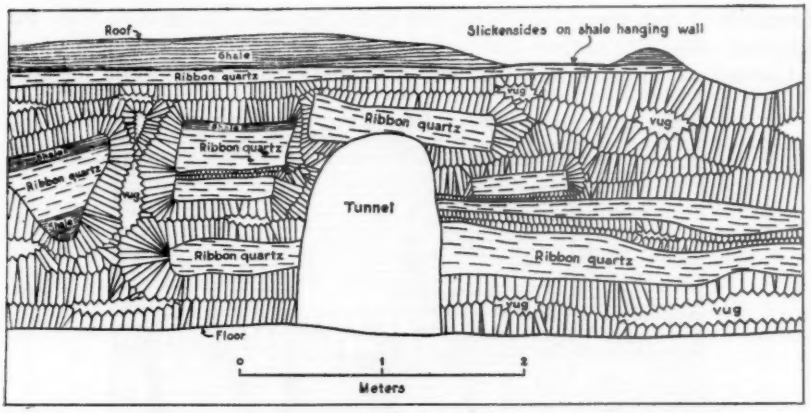

FIGURE 16.—*Sketch of a face in the Silva Regis mine, Mimoso, Bahia*

Showing an earlier generation of ribbon quartz included in later comb quartz.

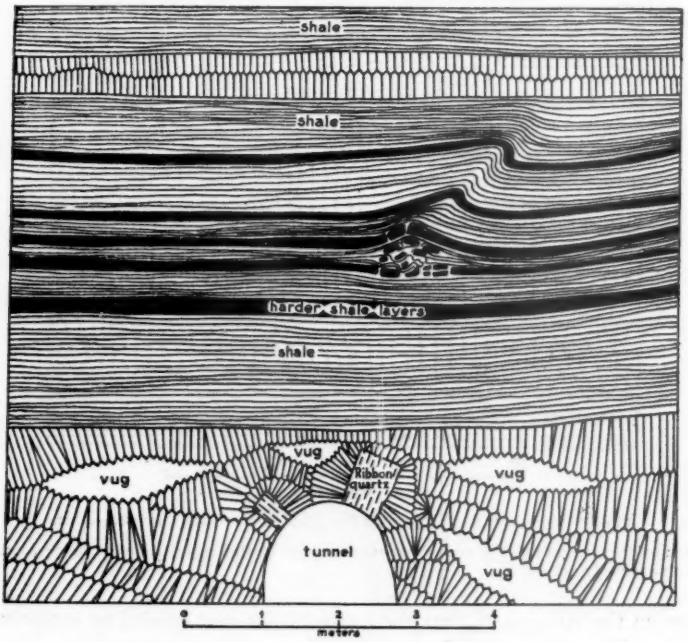

FIGURE 17.—*Sketch of a face in the Silva Regis mine, Mimoso, Bahia*

Showing folding in the shale roof of the lower quartz bed.

veins are lenticular, ranging up to a meter in thickness. Branching from the bedded veins are irregular stockworks of narrow veins that generally cut the sandstone at

low angles. In places, larger and more steeply dipping lenticular bodies, a meter or more in width, intersect the bedding at high angles.

The veins and lenses are filled with comb quartz which grew inward from the walls toward the center (Pl. 1, figs. 1, 2). Most of the quartz is milky. There is, however,

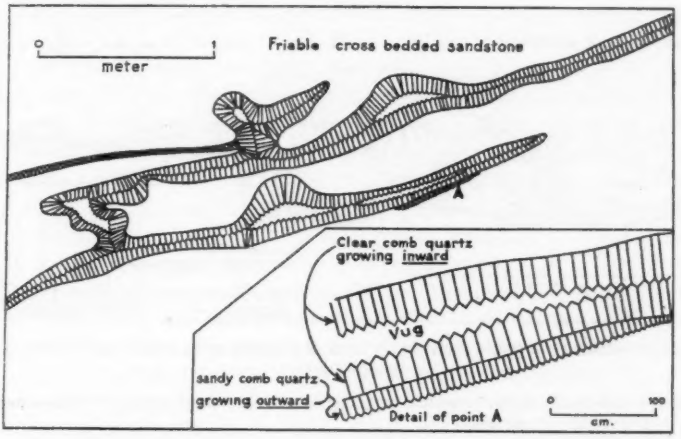

FIGURE 18.—*Sketch of a face in the No. 1 tunnel at Batateiras, Bahia*

Showing clear quartz combs growing inward from the vein walls and quartz combs with sand inclusions growing outward from the vein walls into the sandstone.

a large amount of smoky quartz, ranging in color from a light citrine to a dark brown. Some of the darker crystals are too opaque to be examined in the carbon arc beam. Many of the smoky crystals contain phantoms of darker and lighter quartz, and some show interpenetration twinning, on the Brazil law, of colored and colorless quartz. Although most of the comb quartz grew from the walls toward the center of the vein, crystals growing from the vein walls outward into the sandstone were observed in a few places (Fig. 18). Similar outward-growing crystals were also seen in Minas Gerais (Fig. 19) and Goiaz.

Much of the quartz mined in the area has come from residual accumulations of loose crystals imbedded in sand on the floor of large caves in the sandstone. Some of these caves are 40 by 20 meters in horizontal dimensions and 15 meters in height. Commonly faces of veins show in the walls. The sandstone in the cave walls is soft and friable indicating the loss, by solution, of the cementing material. Solution and cave formation at Batateiras undoubtedly were subsequent to quartz deposition.

At the foot of the sandstone bluff is an alluvial deposit from which came the earlier production of the district (Pl. 11, fig. 2).

Pegmatites.—Pegmatites yield some quartz, but, in comparison with the yield of quartz veins, the quantity is small. Quartz of good quality is found in pegmatities and alluvial deposits derived from them in the states of Minas Gerais, Bahia, Espírito Santo, Rio Grande do Norte, and Ceará.

Pegmatitic quartz can be recognized with certainty only if certain characteristic pegmatite minerals, such as feldspars, micas, or tourmalines are present as inclusions or associated minerals. In the absence of these associated or included minerals, one cannot be certain that a quartz specimen came from a pegmatite.

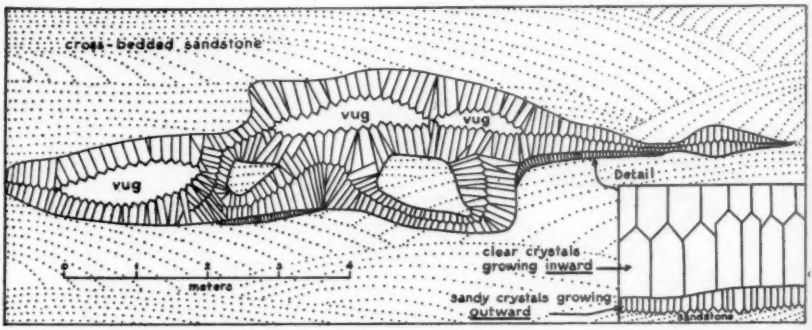

FIGURE 19.—*Sketch of a quartz pocket in the Serra de Lagrinha mine, municipality of Bocaiuva, Minas Gerais*

Showing clear comb quartz growing inward from the pocket walls and comb quartz with sand inclusions growing outward from the pocket walls into sandstone.

An inspection, by Johnston, of most of the mineral collections in Brazil gave the following list of minerals that were found in clear quartz crystals of pegmatitic origin: amphibole asbestos, biotite, chalcocite, chalcopyrite, cleavelandite, epidote, garnet, graphite, hematite (specularite), ilmenite, molybdenite, muscovite, phenacite, pyrite, sericite, topaz, and tourmaline. This list has little significance other than to indicate that any mineral normally occurring in a pegmatite might be found as an inclusion in quartz that crystallized in the final phases of that pegmatite. The inclusion in the list of four sulphides—chalcocite, chalcopyrite, molybdenite, and pyrite—, all from pegmatites in Northeastern Brazil, is of particular interest for it shows that sulphides do not identify vein quartz as distinct from the quartz of the final pegmatitic phase.

After many months of field observations of both pegmatites and quartz veins in Brazil, it has become increasingly difficult to draw a definite line between the quartz phase of the pegmatites and quartz veins. In the highly differentiated pegmatites of Northeastern Brazil (Johnston, 1945a; 1945b; 1945c), quartz was deposited in the final phase where it filled vugs lined with gigantic microcline crystals. In some pegmatites, as at Boqueirão, near Parelhas, Rio Grande do Norte, the quartz filling itself contains vugs that are lined with clear quartz crystals weighing as much as 200 kilos each. In other pegmatites in the same region, apophyses of quartz from the central vug fillings or cores transect the feldspathic and earlier mineral facies of the pegmatites. Such apophyses do not contain feldspar, mica, or other characteristic pegmatite minerals and so far as can be told are essentially monomineralic quartz veins. Pyrite, chalcopyrite, chalcocite, and molybdenite (Rolff, 1944) have been found in the quartz cores of the pegmatites of the Northeast. The quartz of

the pegmatite cores also has abundant liquid-filled vacuoles containing vapor bubbles similar to those formed in the quartz veins. Indeed, there appears to be considerable field evidence to suggest that the final quartz phase of the pegmatites was a hydrothermal process wherein quartz was deposited from dilute aqueous solutions at fairly low temperatures.

Much good quartz, some of which is undoubtedly of pegmatite origin, has come from the region north of Teófilo Otoni, Minas Gerais. Clemente Francisco, on the Rio Mucurí, 24 kms. north of Topázio (formerly called Jardinópolis), is one of the largest mining camps in the region. Most of the quartz has come from alluvial placers in the stream valleys which also yield beryl and chrysoberyl of undoubted pegmatitic origin. Some decomposed pegmatites in the hillsides have also been mined. The Ariranha mine, 30 kms. downstream from the Clemente Francisco, is a series of open cuts in a weathered flat-lying pegmatite that caps a hill. This mine is best known as the source of the large quartz crystal weighing 4.7 metric tons which is on display in the museum in the city of Belo Horizonte.

A small but steady supply of good quartz has come from alluvial deposits in the municipalities of Sta. Leopoldina and Sta. Teresa, Espírito Santo. Part of this alluvial quartz appears to be of pegmatitic origin, for many quartz-bearing pegmatites outcrop in the hills from which the alluvial quartz was derived.

The quartz containing tourmaline needles (Pl. 7, fig. 6) that is found in the swamp-covered alluvium near Aimorés, in Minas Gerais near the Espírito Santo boundary, appears to be of pegmatitic origin (Godoy, 1943). Similar tourmaline inclusions are found in pegmatites near Governador Valadares, Minas Gerais, and at the Poço dos Cavalos mine, Municipality of Cachoeira, Ceará.

A quartz deposit of particular interest because it appears to lie midway between the pegmatites and the veins, sharing some of the characteristics of each, has been described by Smythe (1943). The Zoenina mine is about 15 kms. northeast of Conquista, in southern Bahia. The country rocks are gneisses and quartizites of the Archean crystalline complex. His description follows:

"Twelve different veins, together with several branching veins, have been worked. Although all of these veins have not been productive they are all of the same type. They are irregular, approximately vertical, and vary in strike from N60° E to S70° E. They often pinch from a few meters to a few inches in a distance of two or three meters. In consequence the veins cannot be followed horizontally for any great distance. Although vertical development is insufficient to prove the point it is probable that the veins show the same inconsistency in a vertical direction.

"In practically every case the vein has a selvage of well-crystallized feldspar up to four inches thick along each wall. The feldspar appears to have crystallized on the walls of open cavities as the crystal surfaces facing the center of the vein are perfectly formed. Between the feldspar selvages the vein is commonly filled with "bull" quartz which occasionally contain well formed plates of specular hematite up to two inches across. In a few cases epidote crystals were found attached to the surface of feldspar or quartz crystals. At one point, apparently the remains of an open cavity, there is a deposit of fine grained, soft, dark green, chlorite an inch or two thick on the surface of the quartz crystals.

"Even where the central quartz zone appears massive, a little search usually discovers the presence of crystal faces. These crystals are usually large, individual crystals six feet long and two feet in diameter having been observed. The base of the crystals is usually on the feldspar selvages but the axes of the crystals lie in various positions. There is little doubt but that these crystals grew in open cavities of considerable extent. This is indicated not only by the perfection of many of the terminations but by the fact that open cavities were found in working the veins. One of these was so large that a man could crawl into it for a distance of several meters. In the portion of this cavity still remaining, one wall was composed of the perfectly crystallized feldspar selvage. The other wall consisted of the apices of large quartz crystals.

"Although most of the quartz is milky, and consequently useless, there are occasional clear, transparent individuals."

Other pegmatites having a quartz-filled core which have yielded marketable quartz occur near Jardinópolis (Knouse, 1944b), on the São Francisco River, Bahia.

SECONDARY DEPOSITS

Residual blankets (eluvial).—Residual (eluvial) quartz deposits occur through the crystal-producing regions of Brazil (Pl. 6). They grade on one hand into colluvial and alluvial deposits and on the other into primary deposits in place or essentially so.

Some of the best examples of residual deposits are found at Cristalina, Goiaz, where narrow cappings of residual quartz fragments (Pl. 5, fig. 1) extend for a kilometer or more along fold axes with pockets and veins of quartz crystal in the underlying sandstone. Here, the primary quartz deposits are located by means of the residual quartz blanket. As shown in Figure 9, the residual blanket grades downward into primary quartz, and many fragile vug structures lie essentially undisturbed in deeply weathered sandstone.

Similar residual blankets yielded much of the early production at Pium, Piaus, and Itaporé in Central Goiaz, in many deposits in Minas Gerais and Bahia, and were generally responsible for the discovery of individual quartz deposits throughout Brazil. At Mimoso, Bahia, the limits of the upper bedded quartz vein are marked by the residual quartz blanket. At the Comechas de Meio mine (Fig. 11) in the Serra do Cabral, Minas Gerais, the residual blanket overlying a stockwork of narrow quartz veins has yielded much good crystal.

Many residual blanket deposits are cemented by limonite, whose iron was derived from the weathering of the country rock, sandstones, and shales. Some of these limonite-cemented quartz pavements, called "canga", are so hard as to be mined with great difficulty. More rarely, local patches of gravel are cemented by manganese oxides.

Hillside creep (colluvial).—Where primary quartz, in either veins or pegmatites, crops out on steep hillsides, the material loosened by weathering slides down the hill forming hillside creep (colluvial) deposits. The material is an unstratified mixture of partially decomposed rock and clay containing both complete crystals and fragments of quartz. Generally the quartz is frosted, and the corners are more or less rounded, depending on the distance the material has travelled.

Characteristic deposits of this type are found in the lower slopes of the little mountain valleys near Sta. Teresa, Espírito Santo (Pl. 5, fig. 2). Here weathering of the granites and gneisses is deep, and the hillside creep deposits rarely contain fragments of fresh rock. Most of the quartz is well rounded.

Water-laid (alluvial).—Water-laid (alluvial) deposits occur throughout the crystal-producing areas, but so far as is now known they are best represented in Central Minas Gerais and in Espírito Santo. In general, quartz from stream deposits has a higher ratio of usable material than that from the primary deposits because the shock of colliding fragments during stream transport has tended to break crystals along actual or incipient fractures so that many of those that remain unbroken are sound. The quartz crystals and fragments become rounded (rolados) and frosted so that "windows" must be chipped in them for examination in the field. In Goiaz, such frosted ovoid quartz is called "ovo de Ema", or Emu eggs, after the ostrichlike bird that roams the interior of that State.

FIGURE 1. PAVEMENT OF RESIDUAL (ELUVIAL) QUARTZ
Capping lines of quartz-filled flexures in sandstone. Cristalina, Goiaz.

FIGURE 2. HILLSIDE CREEP (COLLUVIAL) DEPOSIT
Santa Tereza, Espírito Santo.

FIGURE 3. ALLUVIAL DEPOSIT IN A SMALL VALLEY
Santa Maria, Espírito Santo.

SECONDARY DEPOSITS

FIGURE 1. ELUVIAL MINE
Morada Nova, Sete Lagôes, Minas Gerais.

FIGURE 2. ELUVIAL QUARTZ CAPPED BY SOIL
Açudinha mine, Minas Gerais.

RESIDUAL (ELUVIAL) QUARTZ

The Açudinho mine, near Sete Lagôas, Minas Gerais (Fig. 8), is a characteristic alluvial deposit that was laid down in a deep, steeply sloping valley. In a working face 15 meters high, nine layers of coarse gravel separated by beds of clay are exposed. The gravel yields small water-worn quartz boulders, most of which are rounded. Some however, retain their original hexagonal and pyramidal forms.

At the Gameleira mine, 70 kms. north of Curvelo, Minas Gerais, ½ to 1½ meters of coarse crystal-bearing gravel rests on the Bambuí shale. Capping the gravel is a 2- to 6-meter cover of barren red clay. This mine repaid the cost of mechanical stripping.

The mountain valleys near Sta. Maria, Municipality of Sta. Leopoldina, Espírito Santo, contain beds of quartz gravel under a cover of 1 or more meters of clay (Pl. 5, fig. 3). In addition to quartz, the gravel contains rotten boulders of granite and gneiss. The water table in the mountain valleys lies near the surface, and graimpeiro workings seldom exceed 3 meters in depth.

Other alluvial deposits at Cristalina, Goiaz, and Batateiras, Bahia, have yielded much crystal.

SPECIAL MINERALOGICAL FEATURES OF QUARTZ

SIZE OF CRYSTALS

Quartz crystals in the Brazilian deposits range from centimeters to meters in length and from grams to tons in weight. Most crystals in most deposits weigh less than 200 grams, but large crystals are by no means rare.

A piece of completely clear quartz weighing about 150 kilograms was obtained from Itamarandiba, Minas Gerais, by the firm of R. Andrade, in 1940. This, perhaps, is the largest piece of absolutely clear quartz that has been exported from Brazil. Figure 3 of Plate 7 shows a crystal of *A* quality (the highest commercial grade) weighing 66.2 kilograms.

The size distribution of the exportable grades of crystals is indicated in Table 2. Table 2 refers, of course, to trimmed material and not to the original size of the crystals.

Crystals up to a meter in length and weighing several hundred kilos are occasionally found in many quartz deposits. Most of these large crystals are milky, but some have clear portions in the pyramidal zone from which marketable quartz can be broken. Plates 7 and 8 show large crystals from various Brazilian mines.

Perhaps the best known of the larger crystals is that from the Ariranha pegmatite in the Municipality of Teófilo Otoni, Minas Gerais, which is on display in the Feira Permanente das Amostras, in the city of Belo Horizonte. It is 2.2 meters in height, 1.1 meters in diameter and weighs about 4.7 metric tons.

Godoy (1943) described and figured (Pl. 7, fig. 6) a 6-ton crystal about 2 meters in length from the Lorena mine near Aimores, in eastern Minas Gerais, that yielded 1016 kilograms of clear quartz. This crystal was found in a marsh, but, because of the tourmaline crystals which were included in it, it is believed to be of pegmatitic origin. In the same mine, a group of quartz crystals estimated to weigh 110 metric tons gave about 1800 kilograms of clear quartz, a yield of 1.6 per cent.

Crystals weighing a ton or more are common at the Santo Antonio mine in the Serra do Cabral, Minas Gerais; at the Juiz mine, Fazenda do Capão, near Bocaiuva, Minas Gerais; and at the Alegre and Rosilho mines, near Campo Formoso, Bahia. All of these are vein deposits. At the Rosilho mine a vug, 20 meters long and 8

TABLE 2.—*Size of quartz exported from Brazil during 1944*

Size in Grams	Per cent of Total
100/200	34.8
200/300	18.8
300/500	15.9
500/700	9.9
700/1,000	6.1
1,000/2,000	9.0
2,000/3,000	2.6
3,000/4,000	1.2
4,000/5,000	0.7
5,000/7,000	0.4
7,000/10,000	0.3
10,000/up	0.3
	100.0

meters high, lined with well-formed crystals weighing as much as 4 tons each, has been opened.

The largest crystals so far found in Brazil are at Itaporé near Piaus, in north-central Goiaz, where well-formed crystals weighing up to 10 tons are common (Pl. 8). The largest crystal observed was 5½ meters long with a maximum diameter of 2½ meters; its weight is calculated at more than 40 metric tons. So far as known, this is the largest quartz crystal ever found. The entire crystal was milky and did not yield any clear quartz. In the same district, however, several hundred kilograms of clear quartz has been obtained from the pyramidal zone of a single crystal. The large crystals are broken up by drilling and blasting.

TWINNING

Two types of twinning, optical and electrical, are very common in quartz crystals in Brazil. Much clear material is unsuited for use because of twinning on one or both of these laws. Recent papers (Gordon, 1945; Frondel, 1945) give an excellent description of quartz twinning.

Optical (Brazil law) twins are intergrowths of right- and left-handed crystals. Major *r* and minor *z* faces of the twinned individuals correspond. Where ideally developed, Brazil twins can be recognized by the appearance on the same crystal of *s* and *x* faces that are characteristic of both right- and left-handed individuals. However, many crystals having an *s* face on either side of a rhombohedral face are twinned on the Dauphiné law and show twin sutures on the corresponding prism face. Viewed in polarized light in the oil bath of an inspection tank, optical twinning appears as small triangular interruptions of the concentric color rings, which appear when the crystal is viewed along the *c* axis.

FIGURE 1. MILKY QUARTZ FROM ALEGRE MINE, BAHIA

FIGURE 2. VUG LINED WITH LARGE QUARTZ CRYSTALS
Rosilho mine, Bahia.

FIGURE 3. GRADE A CRYSTAL WEIGHING 66.2 KILOGRAMS
Photo by J. C. Wynn.

FIGURE 4. LARGE PYRAMID
Pium, Goiaz. Photo by E. H. Payne.

FIGURE 5. VUG LINING
Piaus, Goiaz. Photo by D. F. Campbell.

FIGURE 6. SIX-TON QUARTZ CRYSTAL WITH TOURMALINE INCLUSIONS
Aimorés, Minas Gerais. Photo by permission of Mineração e Metalurgia.

LARGE QUARTZ CRYSTALS

FIGURE 1. THREE CRYSTALS EACH WEIGHING MORE THAN 3 TONS
Photo by D. F. Campbell.

FIGURE 2. WELL-FORMED LARGE CRYSTAL
Photo by D. F. Campbell.

FIGURE 3. BASAL SECTION OF LARGE CRYSTAL WHOSE PYRAMID GAVE GOOD QUARTZ
Photo by D. F. Campbell.

FIGURE 4. WELL-FORMED CRYSTAL
Photo by D. F. Campbell.

FIGURE 5. SIX LARGE CRYSTALS
With sheeted milky quartz in background.
Photo by D. F. Campbell.

FIGURE 6. CRYSTAL AGGREGATE
Photo by H. Capper Alves de Souza.

LARGE QUARTZ CRYSTALS AT ITAPORÉ, GOIAZ

Electrical (Dauphiné law) twins are intergrowths of crystal with reversed electrical polarity. The twinned individuals are all right-handed or all left-handed. Major *r* faces of one individual are parallel with minor *z* faces of the other. Twinned individuals interpenetrate with irregular contact surfaces. Twin sutures commonly can be recognized by interruptions in the horizontal striations on the prism *m* faces, or by irregular dull areas of *z* in the *r* faces or vice-versa. As all crystallographic axes correspond, electrical twinning is not revealed by inspection in polarized light.

Both types of twinning can be revealed by etching either the natural crystal faces or sawed sections of a crystal. Figure 20 shows sawed basal sections that have been etched. Optical twinning appears as triangular areas bounded by straight lines, whereas electrical twinning shows irregular boundaries. Both types may appear in the same crystal (Fig. 21).

In all the crystal deposits examined, twinning of both types is common.

The vein deposit at Sto. Antonio mine, in the Serra do Cabral, Minas Gerais, yields many crystals in which the *z* face is frosted and the *r* face has a high natural polish. Figure 22 shows two crystals, viewed from the apex parallel with the *c* axis, in which the electrical twin sutures are revealed by frosted areas of *z* in polished areas of *r*. Similar electrically twinned crystals occur at Piaus, Goiaz.

Many colored crystals—citrine, smoky quartz, and amesthyst—show optical twin interpenetrations in which one twin is clear and the other is colored (Fig. 23). Smoky quartz from the Batateiras mine, near Campo Formoso, Bahia; the Juiz mine on the Fazenda do Capão, in the Serra Mineira, Minas Gerais; and a mine near Montes Claros, Minas Gerais, have yielded excellent examples of such color interpenetration on the Brazil twin law. In some twinned amethystine quartz from Jacobina, Bahia, the purple color occurs in one individual but not in the other. Frondel (1945, Fig. 8, p. 460) figures other examples of twinned amethystine quartz. The mineral collection of the American Museum of Natural History, in New York, contains a round gem of 41.20 carats cut from a Brazil twin in which the table shows equidimensional alternating triangular segments of amethystine and clear quartz.

PHANTOMS

Crystals of Brazilian quartz containing phantoms are widely distributed in the mineralogical museums of the world and have often been noted in the literature. Phantoms, although often obscure, are exceedingly common in Brazilian quartz. They represent growth stages of the containing crystal and are outlined by concentrations of vacuoles or included mineral particles or by color variations. Some are very faint and can be seen clearly only when the crystal is immersed in oil and viewed in the beam of a strong light, whereas others are very distinct. Some crystals contain multiple phantoms, whereas others contain a single phantom. In multiple phantom crystals, the phantoms are seldom of the same degree of distinctness; one or two in a crystal are generally more conspicuous than others which may be exceedingly numerous. Improved visualization would undoubtedly disclose additional phantoms, too faint to be seen ordinarily, in most crystals.

In general, phantoms outlined by mineral inclusions are more distinct than those outlined by vacuoles. Phantoms outlined by green chlorite (such as are abundant at Comechas em Cima, Serra do Cabral, Minas Gerais), by white clay minerals (from

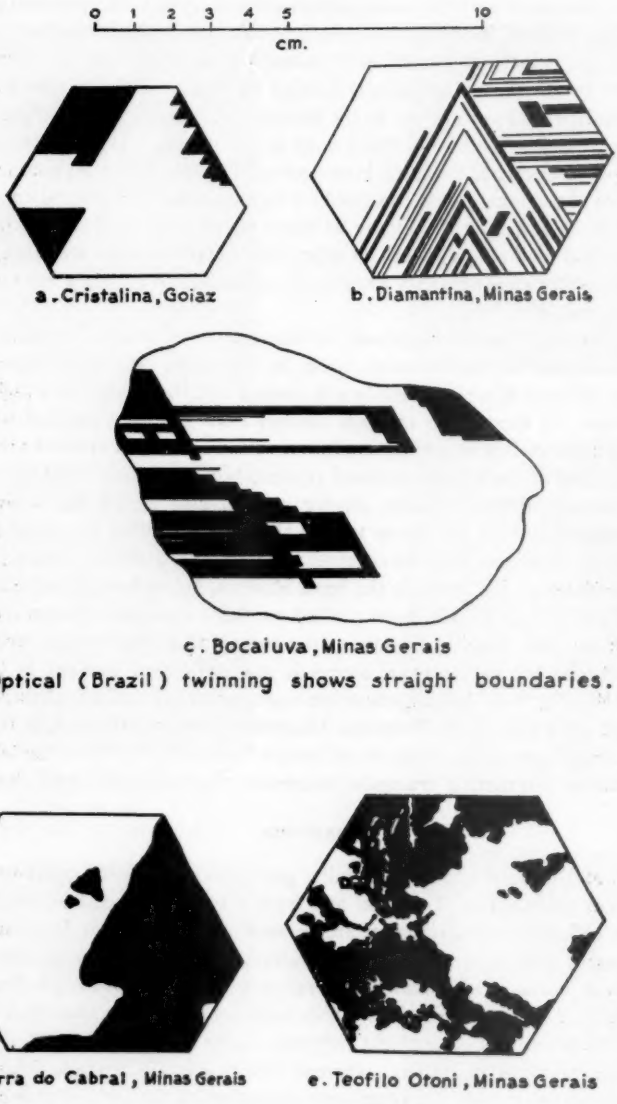
0 1 2 3 4 5 10
cm.
a. Cristalina, Goiaz
b. Diamantina, Minas Gerais
c. Bocaiuva, Minas Gerais
Optical (Brazil) twinning shows straight boundaries.
d. Serra do Cabral, Minas Gerais
e. Teofilo Otoni, Minas Gerais
Electrical (Dauphiné) twinning shows irregular boundaries.

FIGURE 20.—*Optical and electrical twinning in etched sections of quartz*

Santo Antonio mine, Serra do Cabral, Minas Gerais), and black manganese minerals (Alegre mine, near Mimoso, Bahia) are particularly conspicuous.

FIGURE 21.—*Optical and electrical twinning in the same etched section*

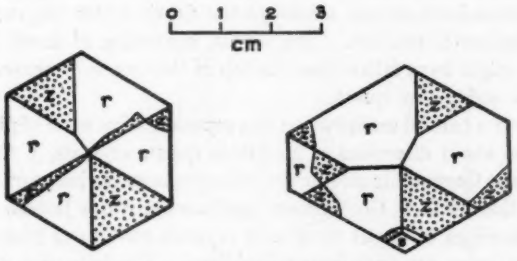

FIGURE 22.—*Crystals showing electrical (Dauphiné) twinning in the pyramidal zone*

Viewed from the apex parallel with the *c* axis. The rhombohedron *r* is clear and *z* is frosted. Santo Antonio mine, Serra do Cabral, Minas Gerais.

In simple crystals, the faces of the phantoms are parallel with the corresponding external face of the containing crystal, although tapering in the phantom due to

oscillatory combination of the prism and rhombohedral faces is usually more acute than on the external prism faces. In doubly terminated crystals, an occasional phantom of the pyramidal cap faces may be nearer the opposite pyramid than the one to which it is parallel.

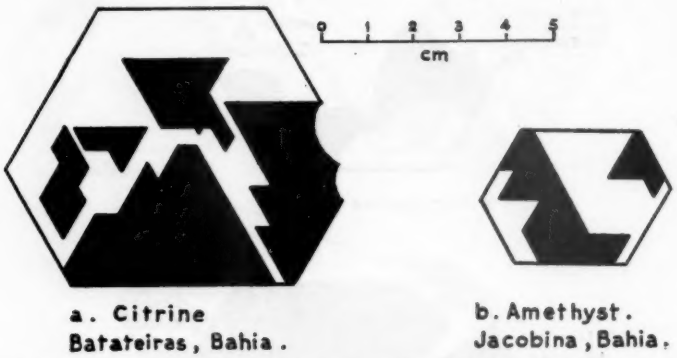

FIGURE 23.—*Interpenetration twins of citrine or amethyst (black) and colorless quartz (white)* Basal sections of optically (Brazil) twinned crystals.

Vacuole phantoms (usually termed bubble phantoms) typically have more complete face development than those marked by included minerals which commonly are incomplete. Many such phantoms show preferential development on one side. Some of the crystals with incomplete phantoms suggest that mineral particles—clay, chlorite, or other material—held in suspension in the quartz-depositing solution settled under the influence of gravity and came to rest on the upper faces of the crystal and did not deposit on the faces that were underneath. A crystal aggregate from Curral Frio mine, near Mimoso, Bahia, that originally formed part of the wall of a vug clearly shows this relationship. Phantoms outlined in clay minerals occur in all of the crystals which make up the aggregate, and, if the aggregate is oriented so that the phantom faces are up, a mass of fine debris within the vug lies on upper surfaces in a horizontal position. The debris, consisting of small broken quartz crystals such as might have fallen from the top of the vug, is cemented by a mixture of clay minerals and glassy quartz.

In the hope that a careful examination of a representative suite of phantoms might yield information about directions of growth in quartz crystals, J. Clarence Wynn, of the Signal Corps Ground Signal Agency, who has been in charge of quality control of quartz inspection for U. S. Government purchases in Rio de Janeiro since 1943, has made careful drawings of about 60 quartz crystals containing phantoms. About half the crystals drawn are from known localities. The following observations are based upon the collection of phantom crystal that Wynn has assembled (Figs. 24, 25).

In multiple-phantom crystals of both vacuole and mineral-inclusion types, commonly one or two phantoms are more distinct than are the others. There appears to

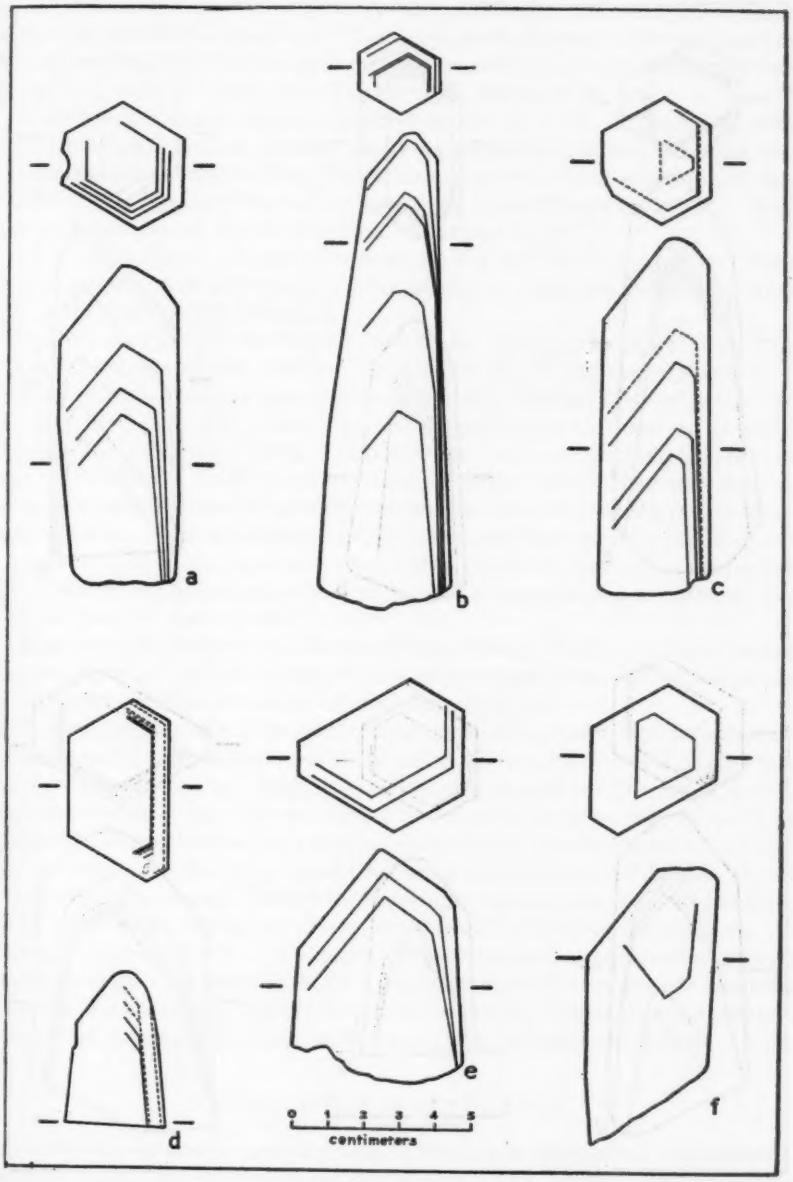

FIGURE 24.—*Phantoms*

Due to coatings of mineral particles marking stages in the growth of the including quartz crystal. After drawings by J. Clarence Wynn.

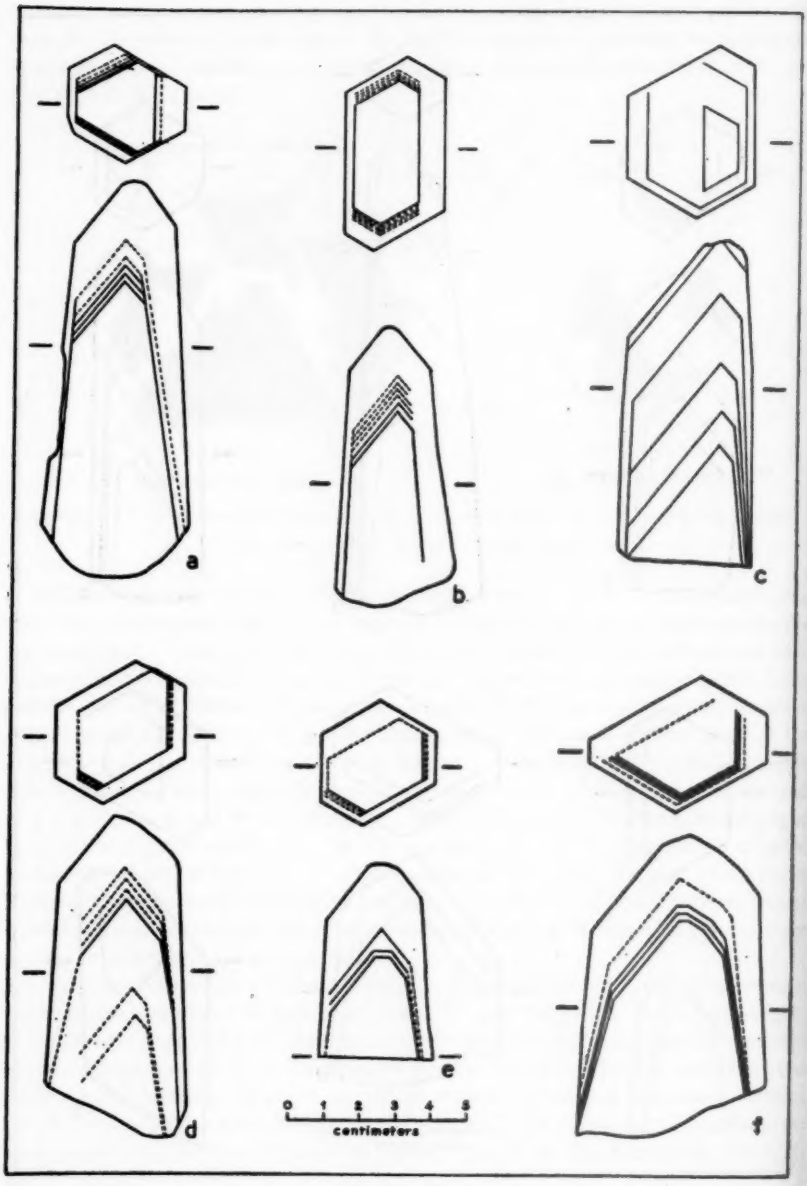

FIGURE 25.—*Phantoms*

Due to mineral particles (solid lines) and vacuoles (dulled lines). After drawings by J. Clarence Wynn.

be no preferred position for the heavy phantoms for they may lie either within or without the less distinct phantoms. The sequence of phantoms reflects the sequence of conditions of crystallization and sedimentation within the vug in which they were formed and probably differs from vug to vug in the same deposit.

In crystals containing phantoms outlined by clay minerals, oscillations of prism and rhombohedral faces on phantom planes are particularly distinct, indicating that the minute shelves resulting from this oscillatory growth offered support to settling particles. The rhombohedral shelves are usually coated; the prisms are not. Preferential adsorption on the rhombohedron might play a part.

As shown in Figure 24, many phantoms are not developed on all faces. These open phantoms, where outlined by included mineral particles, may indicate the upper side at the time of their formation.

In most quartz crystals the rhombohedral *r* faces are larger than the *z* faces. This relation in the relative size of the two rhombohedral faces holds true for phantoms.

Many crystals containing strong phantoms, when examined in an oil bath under polarized light, show optical twinning in the peripheral zone that does not penetrate the most distinct phantom planes. Commonly the quartz lying within the phantom may be untwinned. As the phantoms consist of foreign material that was deposited on faces of growing crystals, probably the coatings induced twinning during subsequent growth. It is well known that the peripheral and apex regions of quartz crystals are more likely to exhibit twinning than are the centers, yet, in the crystals having phantoms, peripheral zones lying outside the phantoms are relatively more twinned than in other crystals.

Many multiple-phantom crystals contain one or two prism faces that are common to several concentric phantoms (Fig. 25), indicating a retardation of the rate of growth of the crystal in a direction normal to these common planes.

In most crystals studied, the general proportions of the final crystal were forecast by the shape of the innermost phantom, and the relative prominence of each face remained constant through progressively developed phantoms. Commonly, growth in a plane normal to the *c* axis was more rapid in one direction so that the center of gravity of the crystal shifted in a progressive and uniform manner, suggesting strongly that the direction of flow of the quartz-depositing solution remained the same during the growth of the crystal. Unfortunately, phantom material was not found in place at any of the mines studied, so information is not at hand about the relation of the direction of crystal growth to the shape of vugs or to positions of individual crystals within the vugs. The prismatic habit of quartz is reflected by the phantom relations —growth was usually pronounced along the *c* axis after formation of the phantom even though the center of gravity in the basal planes conspicuously shifted.

ORIGIN OF THE QUARTZ DEPOSITS

Most of the commercial quartz crystal in Brazil was deposited as vein material. Veinlike bodies show diversified and gradational forms—simple veins, composite lodes, pockets, pipes, stockworks, and bedded veins.

They have the common characteristics that the ratio of clear commercial crystal to worthless but well-formed quartz is low, and the ratio of crystals of the foregoing categories to worthless bull quartz is extremely low. The ratio between commercial crystal and total quartz varies greatly from deposit to deposit. An overall estimate for producing mines is, perhaps, on the order of 1:10,000. In all the vein deposits the clear commercial crystal was formed at a late stage, and almost universally in vugs or open spaces. In most deposits, evidence points to cavity filling as the process responsible for emplacement of the large masses of bull quartz of the earlier stages. The principal indication observed is the directional growth of crystals from the walls toward the centers of the quartz bodies.

Replacement, though widespread in the quartz districts of Brazil, appears to have been but a minor process in most of them. It can be seen in sandstone crystals of Batateiras, Bahia (Fig. 18), and the Serra Mineira, Minas Gerais (Fig. 19), where quartz crystals grew *outward* into the sandstone and not *inward* toward the center of pre-existing cavities. Similarly, remnants of country rock are occasionally found in quartz crystals, but these are mineralogic rarities, whereas, had replacement been the dominant process, they would be abundant. In veins cutting shale, such as in Central Minas Gerais or at Mimoso, Bahia (Pl. 4, fig. 3), inclusions of wall are angular and fresh and show no replacement by quartz.

In the pegmatites, quartz crystallized last and formed cores enclosed by coarsely crystalline microcline. The commercial quartz in the pegmatites generally occurs in vugs within these quartz cores. The pegmatites in the northeast of Brazil (Johnston, 1945a, p. 29, Fig. 4) appear to have been formed in a single cycle of differentiation in which coarse microcline crystals grew outward into a central opening that later was filled by quartz. In many pegmatites, apophyses of the quartz core cut the earlier differentiates of the pegmatites, and outcrops of such intersections, remote from the quartz core, may easily be interpreted as quartz veins cutting pegmatites.

Field studies reveal little difference between the final quartz of a pegmatite and the quartz from veins. Both contain growth phantoms and liquid inclusions, usually with a gas bubble. Rutile inclusions and "blue needles" (which have been variously interpreted as being hollow tubes or linear parting planes) occur in both types of quartz. There appears to be no essential difference in either the type or frequency of optical or electrical twinning, although it is inferred that external structural irregularities accompanying electrical twinning are more typically found in quartz from pegmatites.

Although sulphides are rare in both quartz veins and the quartz core of the pegmatites, more sulphide minerals have been described (Rolff, 1944; Johnston, 1945 a, p. 42) from the pegmatitic quartz of Northeastern Brazil than from the quartz veins of central Minas Gerais, Bahia, and Goiaz. In hand specimens, pegmatitic quartz can be recognized with certainty only if it contains inclusions of pegmatitic minerals, such as mica, feldspar, or tourmaline. It is to be hoped that the study of the chemical character and the degree of filling in the liquid inclusions in various types of quartz, now being undertaken by Dr. Earl Ingerson, of the Geophysical Laboratory, will yield much information about the temperature and pressure conditions under which Brazilian pegmatite and vein quartz were deposited.

The mechanical character of the wall rock influenced the form of the quartz deposits, but there appears to have been no discernible chemical control, for quartz veins are as abundant in Bambuí or Caboclo shales as in Itacolomita or Lavras sandstones and quartzites. Although all of these rocks are silica-rich and were considered by Walls (1919; 1929) and Freyberg (1932, p. 304) to be the source of the silica of the quartz deposits, there appears to be no direct evidence to support that hypothesis, particularly where cavity filling occurred. In certain deposits in sandstone, where replacement features can be discerned, recrystallization of the wall rock, without appreciable migration, might account for the present quartz masses. Quartz deposits have not been found in the limestones members of the Bambuí formation in Central Minas Gerais although many specimens of vein quartz from this region containing cleavage rhombs of calcite have been observed. Not enough is known about the relative sizes of the outcrop areas of limestone and shale within the Bambuí formation in Central Minas Gerais to determine whether the lack of known quartz deposits in the limestones is of genetic significance.

From their study of the quartz deposts at Fazenda Pacú, in Central Minas Gerais, Kerr and Erichsen (1942, p. 498) conclude that:

> "The crystal at Fazenda Pacú has resulted from vein forming solutions. These have forced their way upward along fractures. Crystals have formed in the gouge and in openings in the broken strata at or near the boundary between the Bambuí sediments and the Archean granite. Actual vein forming conditions have probably been similar to those existing in other parts of the world where large accumulations of vein quartz have formed from solution.
>
> "The temperature of formation was probably moderate, the quartz belonging to the alpha phase. It may have formed at temperature considerably below the inversion point. Although not considered pegmatitic, the solutions may have yielded pegmatites at depth. In any event, it seems difficult to conceive of solutions being other than hypogene in a region of such widespread metamorphism."

The writers of this paper are in complete agreement with these conclusions. Viewed broadly, it appears most probable that the quartz deposits of Brazil, both pegmatites and veins, have a single genetic history wherein the pegmatites were more deeply buried at the time of formation and were nearer an inferred parent intrusive than were the veins.

The Brazilian shield is composed essentially of granitic rocks, and Brazil's contribution of strategic minerals during the war years—quartz, mica, beryl, tantalite, and tungsten—are the products of the epigenetic veins, pegmatites, and contact-metamorphic deposits that are an integral part of that dominantly granitic mineralogenic province. Of these economic minerals, quartz appears to be the most widespread throughout the province, and the quartz mineralization in its broadest aspects might be compared with certain "telethermal" deposits, since it lies in little-disturbed rocks, distributed over a great area, and remote from a magmatic source.

AGE OF THE QUARTZ DEPOSITS

Two lines of investigation yield information about the age of the quartz deposits—the stratigraphic position of the veins and pegmatites, and the radioactive minerals contained in the pegmatites. The data now at hand from both lines of investigation appear to indicate emplacement of both veins and pegmatites in Paleozoic time—possibly in the late Silurian or early post-Silurian.

The following is a generalized stratigraphic column of the pre-Mesozoic formations of Brazil.[2]

Permian and Permo-Carboniferous	*Passa Dois series:* shale, siliceous limestones
	Tubarão series: sandstone, shale, coal
	Itararé series: tillite, varved shales, sandstone
Devonian	*Erenê shale*
	Curuá conglomerate
	Maecurú sandstone: sandstone and shale
Silurian	*Bambuí series:* shale, limestone
	Trombetas beds: argillaceous sandstone
Algonkian	*Lavras series:* sandstone and conglomerate
	Itacolomi series: sandstone, quartzite, phyllite
	Minas series: phyllite, quartzite, limestone, itabirite, mica schist
Archean	*Brazilian complex:* gneiss, granite, mica schist, limestone.

Figure 2 is a generalized geological map of Eastern Brazil showing the location of the principal quartz and pegmatite areas. It is based upon the geological map published by the Departamento Nacional da Produção Mineral in 1942.

The principal pegmatite areas in the states of Ceará, Rio Grande do Norte, and Paraíba, in Northeastern Brazil, and in Bahia and Minas Gerais, in East-Central Brazil, are in Archean rocks. The quartz deposits of the Conquista district in Bahia, the Teófilo Otoni district in Minas Gerais and in Espírito Santo, which are in part veins and in part pegmatites, are in Archean rocks. The quartz deposits of the Piaus-Itaporé region, Goiaz, are in Algonkian rocks probably correlative with the Minas series.

The quartz veins of Mimoso and Xique-Xique in Bahia, Cavalcante, and Cristalina in Goias and of Minas Gerais are in Algonkian rocks belonging to the Itacolomi and Lavras series and in Silurian rocks of the Bambuí series. This distribution appears to indicate a stratigraphic gradation between the deeply buried typical pegmatites, emplaced in Archean rocks, and the less deeply buried quartz veins of Central Minas Gerais, Bahai, and Southern Goiaz, which occur in upper Algonkian and Silurian rocks.

No quartz deposits are known in post-Silurian rocks although the upper part of the Paleozoic is fairly well represented in various parts of Brazil. Thus, from somewhat meager stratigraphic evidence, the age of the quartz veins appears to be post-Bambuí (Silurian), and the concept of a transition from quartz veins to pegmatites with increasing depth agrees with the stratigraphic emplacement of the various types of deposits.

Age determinations on seven radioactive minerals from the pegmatites of Eastern Minas Gerais have been published (Hess and Henderson, 1925; Oliveira, 1926; Fenner, 1928; Andrade, 1930; Florencio and Castro, 1943). They are summarized in Table 3.

These age determinations fall into two groups: one, averaging about 360 millions of years, according to our present time scale based on lead age (Keevil, 1941), would be in the Ordovician, and the other, averaging about 530 millions of years, would be in

[2] From the legend of the geological map of Brazil, published by the Departamento Nacional da Produção Mineral in 1942. For more detailed stratigraphy *see* Guimarães (1936) and Oliveira and Leonardos (1943).

the early Cambrian. However, the determination of the age of the Ubá samarskite by Oliveira, based on analyses by Djalma Guimarães, gave 557 millions of years, whereas determinations by Fenner on two samples of samarskite from the same locality gave 340 and 395 millions of years, respectively. In view of these discrep-

TABLE 3.—*Published age determinations of radioactive minerals from pegmatites in the State of Minas Gerais, Brazil*

Mineral	Locality	Author and date	Age in millions of years
Polycrase	Sta. Clara, Pomba	Hess and Henderson, 1925	546
Samarskite	Divino de Ubá	Oliveira, 1926	557
Monazite	Divino de Ubá	Fenner, 1928	360
Samarskite	Divino de Ubá	Fenner, 1928	340
Samarskite	Divino de Ubá	Fenner, 1928	395
Annerodite (?)	Rio Guanhães, Sabinópolis*	Andrade, 1930	352
Uraninite	Engenho Central, Rio Branco	Florencio e Castro, 1943	503

* Andrade reported the annerodite which he analyzed as having come from São Sebastião das Correntes, Conceição do Serro, Minas Gerais. Leonardos (1936), who collected the material, calls attention to the fact that the annerodite came from a pegmatite on the Rio Guanhães, Sabinópolis, Minas Gerais.

ancies, the data at hand do not appear to jusitfy a closer dating for the emplacement of the pegmatites of eastern Minas Gerais than the early Paleozoic.

Johnston has collected radioactive minerals from the pegmatites of Northeastern Brazil and Minas Gerais, and it is hoped that their study will yield new and more precise information on the age of the pegmatites.

The reconciliation of the post-Silurian age of the quartz veins, based on stratigraphic evidence, with an early Paleozoic age of the pegmatites, based on lead-ratio determinations of radiocative minerals in them, does not appear to offer insurmountable difficulties, particularly since the Caledonian revolution, at the close of the Silurian, has long been recognized as a metallogenetic interval in Brazil. Guimarães (1937, p. 2, 74) points out that the limestones and shales of the Bambuí series are cut by veins carrying auriferous sulphides. In speaking of the Caledonian revolution, he says: (1937, p. 74–75): "One must consider the Devonian as the upper limit, in the geological time scale, for phases of magmatic activity characterized by emissions of mineralizing solutions of granitic origin."

Younger granites, cropping our in areas of Archean rocks, that are presumed to be responsible for the Caledonian mineralization have not been dated with certainty, but granitization of Archean schists has been recognized in several regions in Brazil. At present, the best attack on the problem of the age of the granite will be through continued age studies of the radioactive minerals of the associated pegmatites.

MINING METHODS AND COMMERCIAL PRACTICE

Quartz was mined in Brazil in small quantities during the last century, particularly from deposits near Cristalina, Goiaz, and Diamantina, Minas Gerais. Crystals were obtained for museum, jewelry, or ornamental purposes. Quartz, too small for ornamental use, was broken into small chips, called "lasca", and sold for fusing purposes.

Lasca is a manufactured product in the sense that each chip of first quality lasca has been cobbed to the point where no original crystal surfaces are present and no visual imperfections occur. The market for piezo-electric quartz expanded during the 1930's in response to the military demand of both the Axis and Allied Powers. Prices and production increased accordingly (Table 1), and attained a peak in 1943.

Classification of quartz for export purposes is established by the Brazilian Government which publishes an official table (tabella) defining specifications and minimum prices. Stones are classified on the basis of grade (*A*, *B*, *C*, and *D* depending upon the usable quantity of piezo-electric material in each crystal, size (twelve sizes ranging from 100 grams to more than 10 kilograms), and form (faceted and irregular), making a total of 96 commercial categories. For each category an individual minimum price is set upon which taxation is based. Control of exportation is accomplished through official inspectors who certify the quality of shipments to the customs and banking authorities. During the war years, prices on export invoices tended to be well above the minimum prices.

According to law, quartz may be exported from only two ports in Brazil: Rio de Janeiro and São Salvador, Bahia. Production from the interior eventually finds its way to one of these ports, passing through numerous hands en route and utilizing many methods of transport. During the past 2 years, plane transportation has been successfully used by some dealers to carry high-grade material from buying centers in the interior. Crystal from northern Goiaz is carried by mule or truck to the railhead at Anapolis, and, during the rainy season, the 1500-mile round trip by truck from Anapolis to Piaus may take several months.

The major portion of quartz crystal produced in Brazil has been mined by individuals or by small groups working in partnership. The typical miner is called a "garimpeiro" (Pl. 11); he is an individualist and leads a primitive, nomadic existence. His activities are entirely influenced by personal economic conditions. He may abandon the pit in which he is digging quartz in order to wash gold or diamonds or, if food is temporarily scarce, may take to raising the staples of his existence, rice and beans.

The production of a garimpeiro is sold to either a travelling buyer or local businessman, such as a storekeeper. The miner washes the stones which he finds, views them in daylight and trims off the obvious imperfections with a small chipping hammer. The material is then considered "mine clean" and as such begins its travels to the ultimate market. The first buyer collects a considerable quantity of material and then may sell it locally, in a near-by town, or bring it to a port; but in most instances the merchandise passes through five or six hands before exportation. At any stage the temporary owner may clean the quartz by further trimming and eliminate unsuited material through inspection with polariscope or arc lamp in order to obtain a higher-quality, higher-priced product. Large stones which are low grade, upon examination, are trimmed so as to produce a smaller quantity of higher-grade material. The final product for export is thus only part of the mine production. It is estimated that approximately half of mine-clear quartz is suitable for export, although the ratio will vary according to the individual deposit and to the skill and commercial relationships of the producers and dealers involved.

FIGURE 1. ONE-MAN PIT
Porta da Manga, Minas Gerais.

FIGURE 2. PIT WORKED BY MANY MEN USING PRIMITIVE HAND HOISTS
Piaus, Goiaz. Photo by E. H. Payne.

FIGURE 3. PROSPECT CUTS MADE WITH A BULLDOZER
Onça mine, Sete Lagôas, Minas Gerais.

TYPES OF WORKINGS

FIGURE 1. VERTICAL STRINGS MARK BOUNDARIES OF INDIVIDUAL WORKINGS
Itaporé, Goiaz. Photo by D. F. Campbell.

FIGURE 2. DEEP PIT WITH "CHICKEN LADDER"
Pium, Goiaz. Photo by D. F. Campbell.

FIGURE 3. MAN-POWER WHIM AND HOIST
Pinus, Goiaz. Photo by D. F. Campbell.

FIGURE 4. HOISTING WASTE BY STEP-SHOVELING
Cristalina, Goiaz. Photo by R. P. Darnell.

TYPES OF WORKINGS

The classical method in Brazil for mining quartz crystal is by means of pits. In a single district, or "garimpo", hundreds of small pits, each worked by one or two miners, are spread throughout the crystal-bearing ground, and many more exploratory pits may be around the margins. If it is possible for the pits to follow minable ground to depth, benches are left at suitable intervals, which serve as shovel steps (Pl. 10, fig. 4). In a few places, primitive hoisting equipment has been constructed to eliminate the necessity of benches (Pl. 10, fig. 3). In a few large deposits, benched open cuts were evolved, and in some of these more than a dozen shovel steps were present—often as many in the dump material as in the pit. Tools are picks, shovels, hammers, moils, and wedges. One miner with a pick and one with a shovel would be engaged in actual digging at the bottom of the pit or cut, and each shovel step would have its individual shoveler hoisting material up the face and over the dump. Figure 4 of Plate 10 shows an example where four men are working at the bottom of the pit and several times that number are engaged in hoisting the waste.

In many places work comes to a standstill during the rainy season when pit bottoms become flooded. Common dewatering practice is by means of bailing with gasoline tins, passing the tins from man to man either up a chicken ladder or from step to step.

The principal drawbacks to the primitive methods employed are incomplete extraction and slow production. In addition, seasonal labor shortages in the crystal districts occur, and lack of man power decreases the production potential.

In hard-rock mines the usual method of breaking ground is by means of hammer, moil, and wedges (Pl. 9, fig. 1). Extraction in such a property is low, yet many properties of this sort contribute an appreciable part of the total Brazilian production.

Where pits are closely spaced, the waste is piled at the nearest possible point, and the intervening ground becomes muck bound and impossible to work, thereby decreasing the ultimate recovery. At Mimoso, for instance, the operators tried to eliminate lack of ground for waste disposal by constructing dry rock walls to retain the waste. Some of the large individual mines increase their working space through planned disposal of waste. This is usually accomplished through a lease arrangement whereby the groups of miner exploiting the area are under the general supervision of an owner or foreman. Some of the individual leases are for very small working areas, as illustrated in Figure 1 of Plate 10, where hanging strings indicate the limits of the individual concessions. In other places demarcations between groups of workers are marked by thin ribs of rock or soil left standing between the working places.

Quartz deposits have been worked to comparatively shallow depths below the original surface (Table 4).

The reasons for this limit in working depth differ in the various districts. At Mimoso there are no deeper-bedded veins. At Sete Lagôas and at Batateiras, where quartz remains in the bottoms of some of the deeper pits, mining costs determine the economic depth limit by hand methods. At Cristalina, where the deeper pits enter sandstone, the garimpeiros move to new eluvial ground when the sandstone in the old pits becomes too hard to break or when too much water enters. At Piaus, water disposal limits the economic mining depth.

During the war improved mining methods were installed at a number of mines in Minas Gerais and Bahia. The methods and machines employed were relatively simple, and the purpose was to increase the rate of production and realize greater recovery.

Scrapers and bulldozers cleared overburden and removed old dumps which could not have been handled economically by hand; compressors, clay diggers, machine drills, mine cars, buckets, and hoists increased the rate of extraction; and pumps permitted operation during the rainy season. Installations are illustrated (Pl. 2, fig. 1; Pl. 4, fig. 4; Pl. 6, fig. 1; Pl. 9, fig. 3). Several deposits which were exploited by improved methods were successful from the production and financial standpoint. Among these were the Onça and Açudinho mines near Sete Lagôas, Minas Gerais; the Gameleira mine near Corinto, Minas Gerais; the Silva Regis, Alegre, and Batateiras mines, Bahia; and the Serra do Cabral area, Minas Gerais. Others failed to justify the installation of equipment. Various reasons were responsible such as: poor quality crystal, lack of crystal, inadequate supervision, and high cost of transport. In several cases mines which had ceased to be productive through hand operation were restored to productive life for periods ranging from 3 months to 2 years. In general, the conditions governing the operation of quartz mines in Brazil are similar to those encountered in other types of mines throughout the world. There are many small and marginal properties for every large and profitable one.

TABLE 4.—*Maximum present working depths in various quartz areas*

District	Maximum depth (Meters)
Cristalina, Goiaz	15
Mimoso, Bahia	15
Piaus-Itaporé, Goiaz	20
Sete Lagôas, Minas Gerais	25
Batateiras, Bahia	30

In many quartz mines in Brazil, considerable overburden must be removed before gaining access to the crystal-bearing vein, lode, or gravel bed. The ore body itself is composed dominantly of gangue material; in a vein, bull quartz, and in a gravel bed, worthless cobbles. Records indicate that the proportion of mine-clean crystal obtained from quartz mines may vary between 1:1000 and 1:100,000 relative to the total quantity of excavation. The probable average for crystal deposits in Brazil is of the order of 1:10,000. Through selective mining this ratio could be improved. At the Silva Regis mine, Mimoso, Bahia, during a period of bonanza operation, the ratio of mine-clean quartz to total quartz mined reached 1:250. This was one of the exceptional cases where underground operation was feasible and profitable.

Cost of mining crystal ranges from Cr$ 40,00 to Cr$ 200.00 ($2 to $10) per kilogram. The size distribution and quality of the mine-clean product vary from mine to mine and particularly from district to district. Mines producing an undue proportion of small sizes or material known to be low in grade receive a relatively low price for their product, but, on the whole, an average of approximately Cr$ 100.00 per kilogram for mine-clean crystal was sustained in the mining district during the

FIGURE 1. GARIMPEIRO DWELLINGS
At Itaporé, Goiaz. Photo by D. F. Campbell.

FIGURE 2. MINING CAMP AT BATATEIRAS, BAHIA
Viewed from sandstone bluff overlooking town. Alluvial deposits are at left of houses. Gently dipping sandstones in distance belong to Lavras series.

FIGURE 3. TYPICAL GARIMPEIROS AT ITAPORÉ, GOIAZ
Eating their mid-day meal of rice, beans, sun-dried meat, and mandioca flour. Photo by D. F. Campbell.

FIGURE 4. CRYSTAL BUYER AT ITAPORÉ, GOIAZ
Visual inspection in bright sunlight determines value of crystal at mine. More careful examination is made in a darkened room in which sunlight, reflected from a mirror in the street, is focused by condensing lenses set into the house wall. (Note spot of sunlight on the wall.) Photo by D. F. Campbell.

FIGURE 5. CAR FERRY IN GOIAZ
Photo by D. F. Campbell.

FIGURE 6. BRIDGE IN GOIAZ
This type of bridge, characteristic of interior of Brazil, is called a "mata-burro" or donkey-killer. Photo by D. F. Campbell.

LIVING AND WORKING CONDITIONS IN THE QUARTZ DISTRICTS

past 2 years. The average value shown on export invoices during 1944 was Cr$ 250.00 per kilogram of crystal.

The cost of production to the operator varies between wide limits, and a high-cost operation may be financially successful if the quality of the product is good, or if the operator sells directly to the Rio market thereby eliminating intermediate profits, or, as in a few cases, if the producer exports directly. High grading is common and can be understood because of the high value of stones in the larger sizes. A faced crystal weighing 1 kilo might be worth $40 to $50, whereas the daily wage of a miner is $0.50 to 1.00 in U. S. currency. Production records from most mines are inaccurate because of high grading.

RESERVES

The potential reserves of quartz crystal in Brazil appear to be very great, despite the unprecedented volume of production during and immediately preceding the war. The actual (or visual) reserves of quartz crystal are low. The nature of the deposits is not conducive to measurement of reserves, and even during the boom production visible supplies of unmined quartz in any mine, group of mines, or districts have been almost negligible. It is common to walk across a "garimpo" where hundreds of miners asre engaged at work and yet not see a single commercial crystal lying in working faces or bottoms.

Certain prominent mines and some highly productive districts have been virtually exhausted during the war years. For example, production from the high-grade Sete Lagôas deposits has been on the decrease for many months, and the area of good production at Mimoso has been exhausted. The district at Xique-Xique, Bahia, which yielded a large production during 1941, long since ceased to be important. On the other hand, a few newer and more remote districts have come into production. The most recently productive area was in northern Goiaz, where Pium, discovered in 1942, yielded considerable crystal but was successively displaced by the near-by deposits at Piaus and then by those at Itaporé.

In some of the districts or mines which formerly contributed largely, abandonment of the workings was due to exhaustion of the crystal, but in others economic or mining factors caused the abandonment. At places, the mines reached depths where the water or waste could not be handled economically by hand methods. In general, former large deposits close to centers of transportation and population have been depleted.

Enormous areas remain in which prospecting has been superficial or lacking. In most of these areas, mines which produce small quantities of quartz are found, and there are abundant indications of quartz mineralization in the regions. For example, thousands of square kilometers in parts of Minas Gerais are covered with quartz float, and here and there casual prospecting has encountered commercial crystal. In other places, such as northern Goiaz and certain localities in Minas Gerais, where deep soil cover is present over much of the country, float crystal provided incentive for sinking pits, and in some cases production was realized. Large intervening areas of this sort remain for future investigation.

Although reserves of quartz crystal in Brazil cannot be measured, it can be stated

with confidence that the potential capacity for production is still great. Economic factors will govern the production in the immediate future. Under present economic conditions, the visual reserves of quartz in Brazil are not large, but, if any combination of factors tends to increase the financial return to the miner, the incentive to produce will be increased, more "garimpeiros" will immediately begin to work, and new deposits will be found. The epoch of production from the near and readily discovered properties has passed, and production in the future will depend entirely upon prices and conditions that provide incentive for prospecting, that warrant deepening of existing operations, and that encourage the investment of capital in small mining equipment, so as to permit modern low-cost operation of the deposits.

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COMPETENCY OF MOVING WATER TO TRANSPORT DEBRIS

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ABSTRACT

A definition of competence, as related to moving water, is given, and some misconceptions regarding the transporting power of currents are briefly considered.

Data on the competency of currents to support debris in suspension are presented and discussed. A new traction-tube method for studying transportation along the stream bed is outlined. Data from traction-tube experiments are compared with data from the usual flume experiments and are found to be completely integrated.

Finally, some tentative applications of the laboratory data to sedimentation are suggested.

INTRODUCTION

It might seem that a discussion of the ability of moving water to transport debris would have little merit because the underlying principles have been known for many years. Long before geology was recognized as a science, it had been pointed out that the transporting power of running water mounts rapidly with only moderate gains in velocity. Each new flood spectacularly emphasizes the tremendous increase in the amount of debris and the size of particles transported during high water. One cannot fail to be impressed by the fact that the rushing water released by failure of the St. Francis dam in California moved blocks of concrete weighing as much as 10,000 tons.

Yet, curiously enough, geologists have made little practical use of the direct relation between transporting power and the velocity of the moving water. Whenever geologists have attempted to express this relation in the form of a usable law, such as "the transporting power of a stream varies with the sixth power of its velocity", misstatements occur. Admittedly, the transportation of debris, along the bed of a stream or in suspension, is a still unsolved problem. The controlling variables are difficult to evaluate, and probably in no other field of hydraulics have more confusing and contradictory statements been made. However, in spite of many uncertainties, it is felt that the magnitude of a current can be related to the maximum size of a transported particle with sufficient accuracy to be of real use in geological work.

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COMPETENCY OF MOVING WATER AND SOME MISCONCEPTIONS REGARDING IT

Nearly seventy years ago, Gilbert (1876) discussed the transporting power of streams and distinguished between the load carried and the coarseness of the detritus. He pointed out that

> "there is a definite relation between the velocity of a current and the size of the largest boulder it will roll. It has been shown by Hopkins that the weight of the boulder is proportioned to the sixth power of the velocity. It is easily shown also that the weight of a suspended particle is proportioned to the sixth power of the velocity of the upward current that will prevent its sinking. But it must not be inferred that the total load of detritus that a stream will transport bears any such relation to the rapidity of its current. The true inference is, that the velocity determines the limit in coarseness of the detritus that a stream can move, or can hold in suspension."

In spite of the clarity of Gilbert's statement, misconceptions regarding the transporting power of currents have been numerous, and, once these wrong ideas were written into the elementary textbooks, corrective measures were ineffective. For example, Scott (1932) in the third edition of his deservedly popular elementary text states:

> "The transporting capacity of running water varies as the sixth power of its velocity, which means that if the speed of the river is doubled, it can carry sixty-four times as much sediment as before. This very surprising result has been demonstrated both experimentally and mathematically."

Gilbert (1914) called attention to the erroneous version of the "sixth power" law and in the course of his discussion stated:

"About the year 1883 Deacon made, in Manchester, England, a notable series of experiments in the field of stream traction. As the result of definite measurements of quantities of sand transported and of the velocities of the transporting currents, he announced that the amount transported, instead of varying with the sixth power of the velocity, as had been supposed, actually varies with the fifth power."

Deacon (1894) did use the quantity of sand transported, measured by weighing, and he concluded that this varied with the fifth power of the surface velocity of the current.

It is unfortunate that Deacon's conclusion was mentioned by Gilbert because Twenhofel (1932), in his widely used *Treatise on sedimentation*, misconstrues it badly. He says:

"It has been stated that the dimension of a particle which a stream is competent to transport varies as the sixth power of the velocity, but Deacon concludes that the variant is the fifth power of the velocity."

Twenhofel's statement is obviously wrong on two counts: (1) The sixth-power law refers to the mass of a particle and if properly expressed in terms of the dimension of a particle should state the diameter varies as the square of the velocity; and (2) Deacon's conclusion had nothing to do with particle size. These errors are later made even more explicit by Twenhofel (1939) when he states:

"Competency is defined as the ability of currents to transport in terms of dimensions of particles. Competency varies about the fifth power of the velocity."

Numerous additional misconception by other writers are convincingly shown by Quirke (1945).

A stream or current transporting sedimentary materials has, for a given condition, a certain capacity, a definite load, and a maximum size of debris. The capacity is represented by the maximum quantity of debris that can be transported under the given conditions. The load is the actual quantity of debris that is being carried. The load may equal the capacity but usually is smaller. The maximum size of the debris is a reflection of the velocity or transporting power of the current. This maximum size may be less than the current could carry, under the given condition, because larger particles may not be available. If, however, the largest particle is the maximum size the current can transport, under the given conditions, it is then a measure of the competency of the current.

Thus, competence has nothing to do with quantity or load. Competence is measured by the particle of maximum mass that a current is able to transport. If it is assumed that the density of the particles is uniform, all particles composed of quartz for instance, then the competence of a current may be measured by the diameter of the largest particle that can be transported (ignoring, for the time being, the effect of shape of the particle).

Before discussing the data here presented, the writer outlines briefly the relation between the velocity of a current and its competence to support debris, expressed in terms of the diameters of the sedimentary particles.

(1) For all particles large enough to be classed as gravel, the maximum diameter of the individual fragments a rising current can support varies approximately as the

square of the velocity. This is merely another way of stating the much misquoted relation of the mass to the sixth power of the velocity.

(2) For all particles small enough to be classed as very fine sand and silt, the maximum diameter of the individual fragments a rising current can support varies approximately as the square root of the velocity.

(3) For all particles classed as fine, medium, and coarse sand, the maximum diameter of the individual fragments a rising current can support varies between the square root and the square of the velocity. This variation may be expressed as an exponential equation, and for all practical purposes the relation is an increase of approximately 11 per cent in the diameter of a sand grain for each centimeter increase of velocity.

(4) The above generalizations are related to material transported in suspension. After debris has been deposited, and has become a part of the stream bed, a considerably larger current is required to start it moving again.

SETTLING VELOCITIES

Of fundamental importance is the rather obvious fact that the rate at which particles fall in still water must be related to the resistance these particles would offer to transportation by currents. This generalization holds true regardless of whether the debris is transported in suspension or by movements along the bed of the stream. A consideration of settling velocities is therefore essential.

If a particle the size of silt or very fine sand is released in still water it very quickly attains a uniform velocity of fall. This uniform settling velocity is conditioned by the size, shape, and density of the particle; and its rate of fall is resisted by the viscosity of the water. The temperature of the water is therefore important. For spherical particles the settling velocity is expressed by Stokes Law. Rubey (1933a; 1933b) has shown that this may be derived by equating the effective weight of the particle to the viscous resistance of the water, or

$$4/3\ \pi r^3(d_P - d_W)g = 6\pi r\eta v$$

$$v = \frac{2gr^3(d_P - d_W)}{9\eta}$$

where r is the radius of the particle in centimeters; d_p and d_w are the densities of the particle and the water respectively; g is the acceleration due to gravity of approximately 980 cm per sec^2; η is the viscosity of the water in poises; and v is the velocity in cm per sec.

In terms of the diameter of the particles and the settling velocity, Stokes Law may be expressed as:

$$Diam. \propto \sqrt{Vel.} \quad (Diameters\ vary\ as\ \sqrt{Velocities}$$

For particles the size of fine gravel, or coarser, Stokes Law does not hold even approximately. Particles of this size, if released in still water of considerable depth, will be accelerated until they fall with a uniform velocity. The mass of the particle is large enough to overcome the viscous resistance of the water, and hence the ten-

perature of the water is not important. On the other hand, the falling particle tends to leave a turbulent wake, and a streamlined shape, or lack of it, becomes significant.

If we think of a particle of gravel as just being balanced by a rising current, the momentum of the water which strikes it may be represented by $\pi r^2 v^2 d_w$. If this is equated to the effective weight of the gravel particle $\frac{4}{3}\pi r^3(d_p - d_w)g$ and simplified, we get what has been called the Impact Law. In terms of the diameter and the uniform settling velocity finally attained this Impact Law may be expressed as:

$$Diam. \propto Vel.^2 \ (Diameters\ vary\ as\ Velocities^2)$$

For particles the size of fine, medium, and coarse sand the diameters vary between the square root and the square of the settling velocities. Fine sands tend to follow Stokes Law; coarse sands tend to follow the Impact Law; and medium sands follow intermediate values. Later in the paper more explicit terms will be given to this relation of diameters to velocities for the sand-grain sizes.

The above generalizations are accepted by most hydraulic engineers. Supporting data may be obtained from a nomogram by Rouse (1937) and from two excellent papers by Rubey (1933a; 1933b). Geologists, especially those interested in sedimentation, should be more familiar with Rubey's contributions.

REYNOLDS NUMBER

For all practical purposes of this discussion, moving water may be considered to form three flow patterns: turbulent, laminar or streamline, and a combination of turbulent and laminar. The type of flow pattern may be visualized by careful insertion of dyes into the water, or it may be represented by a pure number, whose magnitude does not depend upon the dimensional system used, provided all terms are expressed in units of the same system. This useful ratio has been called Reynolds Number and is designated by R.

In turbulent flow, mass acceleration (inertia effect) is dominant. In laminar flow there is no acceleration, and viscous shear is dominant. Reynolds Number expresses the relative magnitude of the forces involved in mass acceleration and those resulting from viscous shear.

When making suspension tests of debris by water moving upward in an elutriation tube it is desirable to know whether the flow is turbulent or laminar; and, if turbulent, something about the degree of turbulence. For water having a density of 1.0, Reynolds Number gives this information from the following equation:

$$R = \frac{(Diam.\ tube\ cent.)(Vel.\ cent.\ per\ sec.)}{Viscosity\ in\ poises}$$

In general, for any R as large as 2000 the flow will be turbulent, if the elutriation tube has smooth sides. If the tube has been roughened on the inside, turbulent flow will be attained at lower R values.

By substituting the hydraulic radius of a flume for the diameter of the tube, the above equation may be used to determine the flow pattern in model experiments. For R values of 2000 or more, turbulent flow is obtained in the usual straight flume. However, the roughness of the flume bed is also conducive to turbulence, and hence a

bed of gravel may cause turbulent flow even though R may be 200 or less. Any disturbance of the water flowing over the gravel, too large to be quelled by viscosity, will rapidly increase in magnitude, will spread to bordering regions, and eventually will establish fluid turbulence.

Since Stokes Law is dominated by viscous shear, and since the Impact Law reflects mass acceleration, Reynolds Number may also be used to emphasize fundamental differences in the settling velocities of the silts, sands, and gravels. Reynolds Number is obtained by substituting the grain diameter, expressed in centimeters, for the tube diameter in the above equation. For R of about 1, or less, settling is controlled by viscous shear; and the diameters vary as the square root of the velocity. (*See* Plate 1.) For R of about 100, or greater, settling is controlled by mass acceleration; and the diameters vary as the square of the velocity. This again brings out the fact that the smaller the R the greater the influence of viscosity of the water.

EFFECT OF VARIOUS SHAPES OF GRAINS ON COMPETENCY

Thin flakes of mica are kept in suspension by currents more readily than sphercial particles of equivalent mass. Unquestionably, the shape of a particle has a direct influence on its resistance to transportation by moving water. Just how important this effect of particle shape is, however, cannot be readily determined—partly because of a scarcity of experimental data and partly on account of the great diversity of shapes that are represented in sedimentary debris.

TABLE 1.—*Settling rates of various shapes*

Shape	Remarks	Comparative settling (Per cent) rates
Spheres		100
Rollers	Elliptical, egg-shaped forms of different widths and lengths	84–61
Fragments	Very rough but of fairly even proportion	73
Bricks	Rectangular solids	53
Disks	Different thicknesses and cross-section areas	80–38
Cubes		74

Since a sphere gives the highest settling velocity of all possible shapes, it may be taken as a standard of reference. Careful experimental work by Krumbein (1942) on a variety of particle shapes, with constant volume and density, makes possible a percentage comparison of their settling velocities with that of a sphere. Table 1 has been prepared from his data.

From Table 1 it may be reasoned that many particles, because of their shapes, are kept in suspension by currents of from 25 to 40 per cent less velocity than would be required if they were spherical. The particles tested by Krumbein were about the size of large gravel and had Reynolds Numbers of from 3500 to 9000. As previously pointed out, the effect of particle shape becomes increasingly important as Reynolds Number rises above 100. Therefore, it seems quite probable that the above shapes

would show considerably less departure from the settling rate of a sphere, if the particles were the size of sand grains or smaller.

The term shape is here used in a general sense. It is realized that sphericity and roundness are not synonymous, but, since what is desired is an "over-all" picture, no attempt is made to separate the effects of degrees of roundness and angularity from that of sphericity. The settling rates of such shapes as cubes, bricks, and rough fragments reflect not only the geometrical forms of the particles, but also the presence of angularity and a lack of roundness.

For sand-size materials there are few trustworthy data on the relation of particle shape to settling velocity. One way to get around this difficulty would be to use a number of sands having different characteristics and determine how much variation there is, for equivalent grain sizes, in a series of settling tests or suspension tests. With this in mind, 8 different sands were used in the 35 determinations shown in Plate 1, in the part of Curve A that lies in the sand region.

The samples varied from Ottawa sand, with a high degree of sphericity and roundness, to sands whose grains were irregular in shape and angularity. These sands were first sized by sieving, and then the effective grain size of each fraction, separated by elutriation, was determined by measuring the diameters of representative grains with the microscope. Since the plotted data (Pl. 1) do not show much spread it is concluded that the ordinary shapes common to detrital sand-sized sediments have an effect of some 10 to 20 per cent. That is, because of particle shape, the competency of currents to carry sand in suspension may be increased some 10 to 20 per cent. As further substantiation it was found that crushed quartzite fragments, of coarse sand size, required only 85 per cent as large a current to carry them in suspension as was necessary to transport the same size grains of Ottawa sand, which had good sphericity and roundness.

Thus, aside from thin flakes like mica scales, the influence of particle shape in sand-sized material is not preponderant. In general, the further the departure of the shape of any particle from sphericity and roundness, the greater the competence of the transporting current. For silts and very fine sands, the effect of shape may be largely ignored; for sands, the effect may be of the order of 10 to 20 per cent; and for pebbles, some 40 per cent or more.

COMPETENCY OF CURRENTS TO TRANSPORT DEBRIS BY SUSPENSION

GENERAL CONSIDERATIONS

Adjustment of the load of a stream to the velocity of local currents is usually excellent. Through constant alterations of their gradients and beds, by erosion and deposition, streams strive to transport exactly the load of sediment delivered to them.

Even though only a small part of the total energy of a current is used in moving debris, and although currents are seldom loaded to capacity, a moderate change of velocity is generally sufficient to affect the dimensions of particles being transported. The coarseness of the debris is a reflection of the local competency of the stream, provided debris of adequate size is available to the current.

Decreased velocity quickly causes transfer of the coarser material carried in sus-

pension to the bed load; and, at the same time, the coarser part of the latter is dropped and becomes fixed in the stream bed. Increased velocity forces some of the bed-load material to rise and merge with the suspended load. Indeed, all gradations often exist between the suspended load and the material moved along the stream bed, so that suspension may be thought of as a final stage of bed transportation.

Regardless of this close relation, the mechanics of transportation for suspension and bed-load movements are so fundamentally different that they must be discussed separately. Since suspension is better understood, it will be considered first.

PROCEDURE FOR THE SUSPENSION DATA

Eight sands, silts, and gravels of different origin, and having considersble variation in shapes of grains, were carefully screened through the series of sieve sizes shown in Plate 1. Each sieve size was then separated into fractions by elutriation, the velocity of the water measured, the temperature recorded, and the average grain size of each fraction determined by measuring with the microscope. Since the samples were almost entirely of quartz, the data are restricted to detrital material having a density of about 2.65, which corresponds to most clastic material that is transported.

Six elutriation tubes of different cross section were tried during the tests; the two most useful sizes were 3.4 and 4.66 centimeters in diameter. The tubes were straight-sided, 90 centimeters long, with the inlet and outlet openings of 1.8 centimeters diameter flaring quickly to the full size of the tube. Most elutriation tubes commonly used are too short. The tubes used in these tests were long enough to nullify the surge effect at the ends and, more important, made clean-cut grain-size separations possible, because an upper column of 60 centimeters could be entirely cleared of sediment if the velocity of the water was kept constant, for a sufficient length of time.

The valve controlling the flow of water from a constant-head tank reacted positively to small adjustments, so that constant flow of water could be maintained for long periods, and the flow could be changed by a small amount. The quantity of water was determined by catching the outflow from the elutriation tube, for a timed interval of 30 to 60 seconds, and measuring in a graduate to the nearest 5 cubic centimeters. Check determinations were always made even though little variation was found.

Knowing the quantity of water in cc per sec. and the cross-section area of the tube in sq. cm., the average velocity in cm. per sec. follows directly. In addition, dyes were inserted in the water and velocities determined by a stop-watch. For 9 dye determinations, ranging from 9 to 234 seconds required to pass 60 centimeters, the effective cross section area of a tube was 9.0 sq. cm., with a maximum variation of 2 per cent. The measured cross-section area was 9.13 sq. cm.

The temperature of the water from the city main stayed within 1 or 2 degrees Centigrade, after the water had run for half an hour. Also, since most of the tests were made during the winter, the temperature of the water, from day to day, showed little variation. This constancy of the water temperature was important in testing the finer sands and silts, because viscosity changes would have made it more difficult to compare data.

After a sieved sample was placed in the elutriation tube, sufficient velocity of water was used to put the grains in suspension. The velocity was then slowly increased

until some of the grains were carried through the outlet. This velocity was then maintained until the upper 60 centimeters of the tube was free of debris; no samples were taken of the material that was washed through. A slight increase of velocity then moved some grains from the lower part of the tube, and these were caught, and the velocity recorded in centimeters per second. This new velocity was kept constant until the upper 60 centimeters of the tube was again free from all sediment. Another small increment of velocity produced another clean-cut sample. In this way several samples were separated from each sieve size, and the corresponding velocities recorded.

The average grain size of each elutriation sample was determined with a microscope by measuring 20 or more representative grains. If the grains were equidimensional the measurement was easy; but usually the grain shapes were otherwise, in which case the longest and shortest right-angle diameters were measured and averaged. The effect of grain shape on the competency of currents has already been discussed, and, in expressing the average grain size of an elutriation sample in millimeters, the influence of shape is somewhat concealed. On the other hand, the samples were all sized by sieving, before further separation by elutriation, and the sieving operation must have been influenced by the grain shape.

By following this procedure , duplicate checks could be made consistently on the relation of grain diameter to velocity of the water.

DISCUSSION OF THE SUSPENSION CURVES

In Plate 1, Curve A represents the diameters of the grains in millimeters plotted, on logarithmic paper, against the velocity in cm. per sec. of the current just sufficient to support these grains in suspension. The curve is based on a water temperature of 5° Centigrade. Also shown are the mesh openings of the sieves used, in millimeters; the velocity of the current in feet per second and miles per hour; the size range of the different types of debris; and the magnitude of Reynolds Number for grain diameters.

Equations of the general form $y = cx^a$, if plotted on logarithmic paper, make a straight line. The exponent a may be determined by measuring the slope of the line. Curve A is a straight line for the silt and fine sand sizes, with a slope of 1:2; curve A forms another straight line for the gravel, with a slope of 2:1. Recasting these two straight-line segments of the curve in the form of the general equation above we get

$$y\ (diameter) = cx\ (velocity)^{1/2}$$

$$Diam. \propto \sqrt{Vel.}$$

and

$$y\ (diameter) = cx\ (velocity)^{2}$$

$$Diam. \propto Vel.^2$$

In other words, the velocity of currents required to support silt and fine sand in suspension follows Stokes Law; for gravel it follows the Impact Law.

The swing of the curve between Stokes Law and the Impact Law, in the sand region, may be better understood if the data are replotted on semilogarithmic paper. This has been done in Figure 1. Diameters in millimeters are plotted on the y axis (which

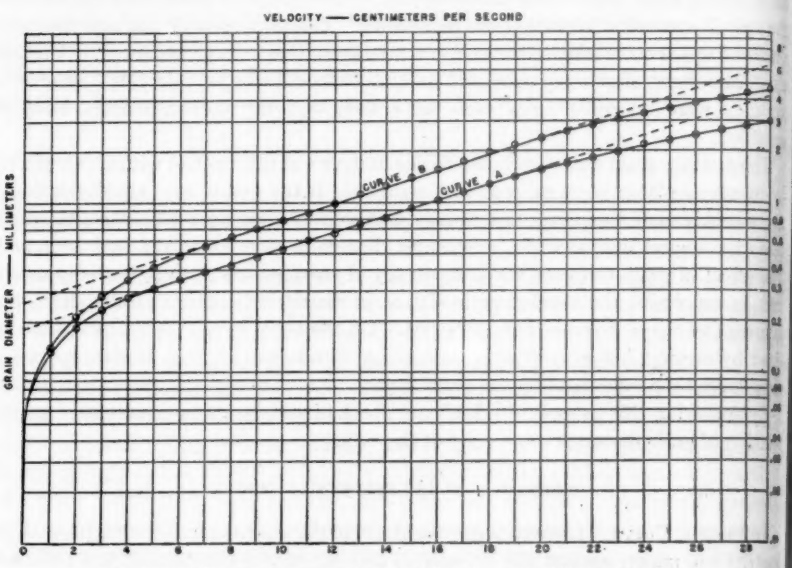

FIGURE 1.—*Suspension curves A and B plotted on a semi-logarithmic base*

A straight-line relation is present in the sand region. Expressed in terms of competency, this is equivalent to an 11-per cent increase in the diameter of a sand grain for each increment of 1 centimeter in velocity.

varies geometrically), against velocity in cm. per sec. on the x axis (which varies arithmetically).

A straight-line relation is present in the sand size region, and may be expressed in terms of an exponential equation of the general form $y = ce^{ax}$. This may be written $\log_e y = \log_e c + ax \log_e e$; and, by substituting data from the straight-line part of the curve, a value of 0.11 is obtained for the exponent a. The general equation may now be expressed as $y = ce^{0.11x}$, which means that for each increment of 1 centimeter in velocity the diameter of the sand grain increases approximately 11 per cent.

Velocity distribution in any cross section of a stream is very irregular and unequal. A considerable fraction of the suspended load would settle out rather readily, were it not for these random and rapidly changing threads of velocity. Leighly (1934) pointed out that each thread of maximum velocity is accompanied by two threads of maximum turbulence. If the suspended material diffuses into a region of less turbulence and decreased velocity, some of the debris will be deposited. Any other relation, however, will tend to keep the material in suspension, as, for instance, diffusion into an area of less velocity but greater turbulence, or into one of greater velocity and less turbulence. The degree of turbulence, therefore, must be allowed for in addition to velocity. The role of turbulence in keeping material suspended has been empha-

sized by O'Brien (1933; 1936), Cook (1935), and Kalinske (1942); and it is generally recognized (Hjulström, 1935; 1939) that fluid turbulence is practically always present in all natural currents, even the low-velocity currents of the ocean.

Data for curve A were obtained by using elutriation tubes with smooth sides. Visual inspection during the tests indicated laminar flow for suspensions of the finer sands, and a mixture of laminar and turbulent flow for the coarser sizes. By calculating Reynolds Number for tubes, and using 2000 as the division point between laminar and turbulent conditions, it was possible to determine approximately the type of flow for each test. This has been shown in Plate 1. The noticeable interfingering of laminar and turbulent flow results from using elutriation tubes of several diameters. Also, some of the tests marked laminar probably were in part turbulent. Moreover, the degree of turbulence was not great, even for the gravel particles. Obviously, curve A cannot be applied precisely to suspension by stream currents, since some degree of turbulance is practically always present under natural conditions.

In order to obtain turbulent flow at low velocities, the smooth-sided elutriation tubes were modified. The glass was softened by heating so that indentations could be punched into the outer wall deep enough to form rounded mounds on the inner wall. These projected from 0.5 to 1.0 centimerer and were scattered irregularly around the tube, from 4 to 6 centimeters apart. Seven velocity dye tests were run, to calibrate each corrugated tube, over a time-interval range from 10 to 150 seconds. The effective cross section area could be checked within 2 per cent, and this determined cross section was then used to find the velocity at higher flows.

Curve B (Fig. 1; Pl. 1) is the result of suspension tests made with corrugated tubes. The greater efficiency of turbulent flow in supporting suspended material is obvious, because otherwise curve B (temperature 10° C) should lie below and to the right of curve A (temperature 5° C). It is felt that curve B may be used as a reasonable basis for estimating the velocity of currents required to support debris in suspension under natural conditions. These currents are the random and rapidly changing threads of velocity and turbulence, previously mentioned, that are responsible for keeping the sediment in suspension.

The main suspended load of a river is silt and clay, and the clay content is largely independent of current velocity and turbulence. During floods very fine sand may be carried by rivers in suspension, which indicates velocities of supporting currents in the neighborhood of 1 centimeter per second. Mountain streams, during high-water stages, may carry coarse sand in suspension, which indicates the presence of supporting currents with velocities up to about 10 centimeters per second. However, aside from the fact that increased stream flow gives greater turbulence and mixing of the water, the horizontal velocity of the stream is not a measure of the suspending currents.

COMPETENCY OF CURRENTS TO TRANSPORT DEBRIS BY TRACTION

GENERAL CONSIDERATIONS

As a result of Gilbert's (1914) research, it was established that movement of the bed load of a stream, by the tractive force of a current, is quite complex. Although

many investigations have been undertaken since that pioneer contribution, the problem is still far from solved.

Most of the work has been carried on in hydraulic laboratories where good-sized flumes and large supplies of water are available. A flume has many advantages; but it is not easy to measure and maintain the slope of the water surface, the slope of the bed, the depth of water, and the character of the bed during a test run in a flume. Also the equipment is cumbersome, and usually the services of more than one person are required. An attempt was made, therefore, to devise a different method of testing.

It is suggested that the following procedure may be used to advantage in demonstrating, to students of sedimentation, the transport of debris by traction. No expensive equipment is required, and, as will be shown, the results obtained are comparable to flume experiments.

PROCEDURE FOR THE TRACTION DATA

An ordinary pyrex tube, 90 centimeters or more long, and with an inside diameter of 2–6 centimeters, was used instead of a flume. A half cylinder of wood or steel, having a cross section half that of the tube and a length of 6–12 centimeters, was cemented in each end so that the upper flat surfaces were exactly parallel.

One end was stuffed with cheese cloth until even with the inside end of the half cylinder, and the tube was then filled exactly to the middle mark with a sample. The other end was stuffed with cheese cloth, and the tube was then rolled slowly, back and forth, on a level table top. This distributed the sample evenly and formed a smooth, level bed, which was finally brought parallel to the smooth surfaces of the half cylinders.

A rubber hose was then slipped over one end and the tube clamped in a level position. Water was allowed to enter slowly so as to displace the air in the sample, and minor adjustments were made in the position of the tube so that the sand bed was level from side to side, as well as from end to end. The flow of water was increased until the traction tube was filled and all air bubbles driven out. At this stage, the water should be moving at a speed less than the critical velocity necessary to transport any part of the sample. If any grains are moved before the tube is completely filled with water, a tube of different diameter should be used, or a stop-cock may be connected to the outlet, and a back pressure produced.

One obvious advantage of this set-up is that small slopes of water surface and bed surface do not have to be measured and do not have to be maintained at a constant value during a test run. The velocity is determined by a constant-head tank and a positive control valve; and, since the bed is level and the top of the tube parallel to it, slopes do not enter. Moreover, the bed is visible throughout its length, sides as well as top, and any changes in the bed may be quickly measured with a pair of calipers.

COMMENTS ON THE MOVEMENT OF THE BED LOAD

The different ways by which the bed load is transported were first described by Gilbert (1914). Bed-load debris progresses downstream, at a slower rate than the transporting current, by rolling, jumping (saltation), and sliding. For short intervals the material may even be in suspension. The particles may travel as scattered indi-

viduals, or in groups and clusters, or in rhythms and ripples, or the entire surface of the bed may be in irregular motion. Increases in the velocity of a current usually result in the following successive stages of debris movement—scattered transport, smooth transport, dune-ripple transport, smooth transport, and antidune-ripple transport. All of these methods of bed-load movement, except antidune-ripple transport, can be studied in the traction tube.

(1) *Initial movement.* No matter how carefully the sample was rolled, back and forth, in the traction tube, the resulting bed was never perfect, although it appeared to be smooth and level. As the velocity of the water in the traction tube approaches a critical magnitude, a few grains are moved from points on the bed that were a trifle high and dropped in the nearest slightly low area. No sediment is carried the length of the tube.

(2) *Scattered transport.* A further slight increase in velocity will cause a few grains to move, scattered here and there in different areas of the bed. Some sediment will appear at the discharge end of the traction tube, and this debris usually represents the larger grains of the sample, especially if the sample is of fairly uniform grain size. However, if the sample is composed of diverse grain sizes, the smaller particles will be transported first because of the winnowing action of the current. The degree of transportation may be characterized as weak.

(3) *Smooth traction.* An additional slight increase in velocity will cause the movement of more grains, often in groups and clusters. The degree of transportation may be classed as medium. For coarser sands and gravels a further increase in velocity will cause smooth traction throughout the entire bed surface, without the formation of dune ripples.

(4) *Dune-ripple transport.* If the debris is finer than coarse sand, the early smooth traction phase is usually not important because ripples are formed too readily. In general, the finer the sand the better the ripple production. Ripples may form most readily in the medium to finer sands because of the effect of the film of laminar flow next to the surface of the bed. The larger particles of coarse sand and fine gravel project far enough above this film to be swept along by smooth traction.

A current ripple originates because of localized deposition. In fact, a ripple progresses downstream as a result of continuous deposition, of traction-rolled debris, on the downstream face of the ripple form. This is easily seen in the traction tube if the current is just sufficient for initial movement and scattered transport of the medium or fine sand grains. This debris is never moved very far but is dropped into the nearest slightly low area. A small pseudo delta is formed when several grains are deposited at the same place. Once this is established, it is made more prominent by the deposition of further sand grains as fore-set beds. After grains have been rolled along the top-sets of the pseudo delta and dropped on the fore-sets, the current, as it swings down over the fore-sets, develops an eddy swirl, and, since it is underloaded, a scour is soon formed in the lee of the ripple. The debris picked up by this scour is quickly dropped, and another pseudo delta is established at a definite distance downstream.

This new ripple determines the position of another one still further downstream; and it is not unusual to see six or more pseudo deltas appear, one after the other—each

slowly progressing downstream by continuous deposition on the downstream face of the ripple form. No transported debris appears at the outlet until one of the delta forms has reached the discharge area. If the initial current had been slightly greater many ripples would have appeared, almost simultaneously, throughout the length of the traction tube.

(5) *Smooth traction.* A further increase of velocity will cause some of the grains, which are rolled along the top-sets, to jump over the fore-set zone of deposition and continue rolling toward the next ripple. With a further slight increase of velocity deposition on the fore-sets will cease, and the current no longer will sweep down over the fore-sets but will jump to the next ripple, causing erosion of the ripple tops. Quickly, the ripples will disappear, and the entire bed surface will be in a state of smooth traction. This is the most efficient stage of bed transportation, and from this stage it is relatively easy for some of the finer particles to go into suspension.

(6) *Antidune-ripple traction.* In this stage the ripple form progresses upstream against the current. The shape of the ripple is nearly symmetrical. Most investigators have concluded that the antidune stage occurs only with shooting flow or jet flow, and that it is seldom observed in nature.

In the writer's opinion, antidune ripples are a natural result of scour and tend to occur wherever the gradient of a stream bed is being reduced by cutting. This may be readily demonstrated in a flume. Suppose a current is loaded with sediment so that the stream bed is built up by deposition, with a consequent increase of gradient. Then suppose the load is decreased, or the current increased, The underloaded stream will immediately secure additional load from its bed, a scour will develop and will move rapidly upstream. After the scour has passed the gradient of the stream will have been reduced. It is not unusual to find four to six scours—the antidune ripples—produced simultaneously, following one another upstream, and each scour reducing the gradient of the stream bed as it passes. Antidune ripples are not restricted to shooting flow or jet flow, but, since they are a type of scour attendant on reduction of bed gradient, preservation of the ripple form is infrequent.

DISCUSSION OF THE TRACTION DATA

Unfortunately, there is no agreement as to the best way of measuring and expressing the force required to move debris along the bed of a stream. One difficulty is the presence of a thin zone of laminar flow, with a velocity of zero at the stream bed, and a steep velocity gradient to the top of the zone where turbulent flow exists. Moreover, it is not possible to measure bed velocities directly, because the placing of any measuring device, on the stream bed, completely upsets the flow pattern.

If the velocity gradient could be measured immediately adjacent to the stream bed, the effect of the differences of pressure, above and below the center of a sand grain, could be calculated. Overturning and rolling of the sand grain would occur at a certain critical value. O'Brien (1936), MacDougall (1933), and Hjulström (1939) have emphasized the importance of the velocity gradient in movements of the bed load. In addition, Kalinske (1942) points out that at low Reynolds Numbers the force of the current on the stream bed is predominantly tangential, and at higher Reynolds Numbers this force is dominantly normal. This results in a vertical shift

of the resultant line of action of the fluid force on the sand grain, and transportation is a natural consequence.

To get around the impossibility of measuring bed velocities, many hydraulic engineers use the frictional drag of the current upon the stream bed. This is the familiar "critical tractive force" law and is usually expressed in pounds per square foot. It may be computed from duBoys equation

$$T = \rho Ds$$

where ρ is the unit weight of water, D is the depth of water, and s is the slope. This basic equation has been modified by Kramer (1934) and O'Brien and Rindlaub (1934).

Of course it is not practical to use duBoys equation to calculate the critical tractive force in any traction-tube experiments since slopes are not present. The most comprehensive flume study on bed transportation, with which the writer is familiar, is that published by the United States Waterways Experiment Station at Vicksburg, Mississippi (1935). Table 2 is based on their experimental data, and the critical tractive force has been computed from duBoys equation. Because these include only one gravel sample, additional data for the coarser debris are taken from the work by Gilbert (1914) and are shown in Table 3. Again the critical tractive force is calculated from duBoys equation.

In Figure 2, the average grain size has been plotted against the critical tractive force. It appears that the competency of a current to transport the bed load, as measured by the grain diameter, varies through a considerable range with the critical tractive force of that current. That is, straight lines drawn through adjacent points on the critical tractive-force curve (Fig. 2) indicate exponents decreasing more or less uniformly from 2.0 to 0.5 , and averaging about 1.0.

This method of expressing bed transportation is not very useful to geologists because information on slope and depth is often not available. Also, measuring bed transportation in pounds per square foot conceals the relation of bed load to suspended load, since the latter is measured in terms of supporting current velocities. Both suspension and traction should, if possible, be measured in the same units.

The impact or momentum of water against debris lying on a stream bed also results in transportation of the sediment. Thus, actual current velocities, as well as velocity gradients, are important. It would seem, therefore, that average current velocities taken near, but not directly on, the stream bed should be of considerable value. Admittedly, such velocities would be greater than the actual bed velocity. For convenience, they may be termed critical-traction velocities.

In a flume experiment, for example, the average velocity of the current that just moves the sediment on the bed should be approximately the critical-traction velocity, provided the depth of water is small. Or, the average velocity of the current in the traction-tube experiments should give a comparable critical value because the depth of water in the traction tube is small. In streams and rivers, average velocities measured a few inches above the bed would be of similar character.

The data in Table 4 are from a series of traction-tube experiments conducted as previously outlined. The data in Table 5 are averages of the same flume tests as Table 2, made by the United States Waterways, at Vicksburg (1935). The data

TABLE 2.—*Critical tractive force**

Grain diam. (millimeters)	depth (feet)	Slope	Tractive force (lbs. per sq. ft.)	Sand movement
4.0769	.305	.0030	.0571	medium
4.0769	.252	.0040	.0629	medium
4.0769	.232	.0045	.0651	medium
4.0769			.062	
.5861	.127	.0010	.0079	medium
.5861	.071	.0015	.0067	medium
.5861	.063	.0020	.0079	medium
.5861			.0075	
.5409	.131	.0010	.0082	medium
.5409	.114	.0015	.0107	medium
.5409	.072	.0020	.0090	weak
.5409			.0093	
.5246	.117	.0010	.0073	medium
.5246	.087	.0015	.0081	medium
.5246	.066	.0020	.0082	medium
.5246			.0079	
.5056	.132	.0010	.0083	medium
.5056	.081	.0015	.0076	medium
.5056	.078	.0020	.0097	medium
.5056			.0085	
.4828	.120	.0010	.0075	medium
.4828	.080	.0015	.0075	medium
.4828	.066	.0020	.0082	medium
.4828			.0077	
.3470	.091	.0010	.0057	weak
.3470	.061	.0015	.0057	medium
.3470	.048	.0020	.0060	weak
.3470			.0058	
.3104	.108	.0010	.0068	medium
.3104	.054	.0015	.0051	weak
.3104	.049	.0020	.0061	weak
.3104			.0060	
.2053	.075	.0010	.0047	medium
.2053	.051	.0015	.0048	weak
.2053	.034	.0020	.0042	weak
.2053			.0046	

* Data from U. S. Waterways Experiment Station, Vicksburg, Mississippi (1935).

TABLE 3.—*Critical tractive forces**

Grain diam. (millimeters)	Depth (feet)	Slope	Tractive force (lbs. per sq. ft.)	Sand movement
H 6.08	.171	.013	.139	medium
H 6.08	.184	.013	.149	general
H 6.08	.141	.0205	.180	medium-general
G 4.18	.095†	.02†	.118†	medium
F 3.08	.093	.01	.058	weak-medium
E 1.38	.05	.0113	.035	general
E 1.38	.07	.005	.022	general
D 0.72	.357	.00078	.017	weak
D 0.72	.392	.00045	.011	weak

* Data from Gilbert (1914, Tables 9, 10, p. 69, 70).
† Average of eight runs (Table 10, sand size G, runs 9, 15, 19, 22, 23, 28, 40, and 43).

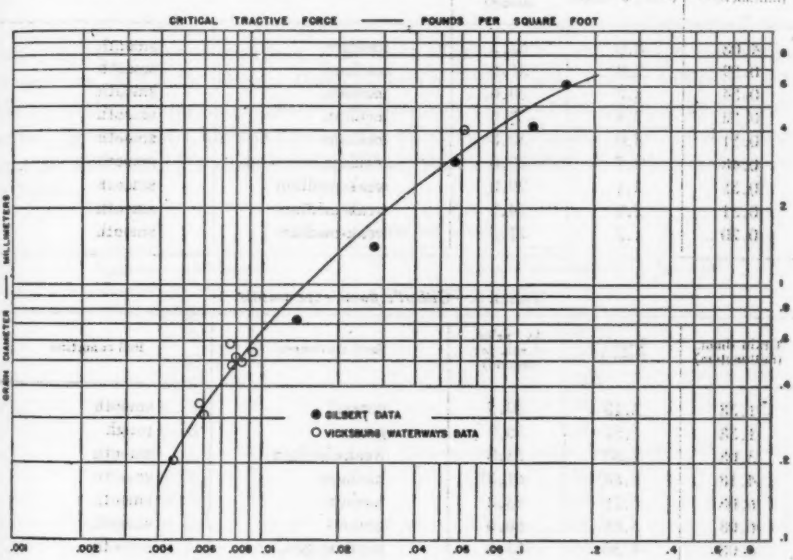

FIGURE 2.—*Critical tractive-force curve*

in Table 6 are from Gilbert's (1914) famous flume experiments in California and are the same runs as shown in Table 3.

In Plate 1 the critical-tractive velocities have been plotted against average grain diameters, and a critical-traction velocity curve has been drawn. A study of the plotted data and the traction curve brings out the following significant points:

TABLE 4.—*Traction tube experiments*

Grain diam. (millimeters)	Depth (cent.)	Av. veloc. (cent. per second)	Sand movement	Bed condition
3.25	1.7	59.5	general	smooth
2.25	0.94	49.6	general	smooth
1.20	1.0	40.0	general	smooth
0.91	1.0	33.0	general	smooth
0.80	1.25	32.8	general	smooth
0.61	0.94	30.0	general	smooth
0.45	1.1	31.2	weak-medium	smooth-dunes
0.35	1.1	26.8	general	smooth-dunes
0.32	1.0	22.5	medium	smooth-dunes
0.30	1.7	24.4	general	dunes
0.21	1.2	23.6	medium	dunes

TABLE 5.—*Vicksburg Waterways flume experiments*

Grain diam. (millimeters)	Depth (cent., average)	Av. veloc. (cent. per second)	Sand movement	Bed condition
4.08	8.0	62.2	medium	smooth
0.59	2.9	31.6	medium	smooth
0.54	3.3	30.6	medium	smooth
0.52	2.8	28.6	medium	smooth
0.51	3.0	30.8	medium	smooth
0.48	2.7	29.8	medium	smooth
0.35	2.1	29.0	weak-medium	smooth
0.31	2.0	24.5	weak-medium	smooth
0.20	1.5	21.5	weak-medium	smooth

TABLE 6.—*Gilbert's flume experiments*

Grain diam. (millimeters)	Depth (cent.)	Av. veloc. (cent. per second)	Sand movement	Bed condition
1.38	2.13	40.5	general	smooth
1.38	1.52	36.0	general	rough
3.08	2.83	53.8	weak-medium	smooth
4.18	2.88*	61.3*	medium	smooth
6.08	5.21	83.2	medium	smooth
6.08	5.61	86.6	general	smooth
6.08	4.30	83.6	medium-gen.	smooth

* Average of 8 runs.

(1) Complete integration of the traction-tube data with the precise flume data demonstrates the value of the simpler traction-tube experiments.

(2) Comparison with the critical-traction force curve and data of Figure 2 shows that the grain diameters (competency) are arranged in the same order, whether measured by critical-tractive force or by critical-tractive velocity.

(3) The bed velocities that are actually transporting must be closely related to the plotted critical velocities because the data are so consistent.

(4) Competency, as measured by grain diameter, varies with the 2.6 power of the critical-traction velocity, indicating that the impact of the water is important in bed transportation.

(5) In contrast to the transitional relation for settling velocities in the medium sand grade, the velocity-squared (actually Vel.$^{2.6}$) relation holds true for traction transportation down through coarse and medium sand, and at least part way into the fine sand grade.

A final step that could be undertaken would be to penalize or reduce the critical-traction velocity a certain amount so as to make it more nearly equivalent to the effective bed velocity. For instance, Hjulström (1935) suggested that the bottom velocity would be about 40 per cent less than the average velocity. An ingenious method of estimating bed velocity has been suggested by Rubey (1938). In his equation

$$V_b^2 = \left[1.05 \log \frac{r}{R} + 3.11\right] \sqrt{g}\, V_m \sqrt{rs}$$

V_b is the bed velocity, r is the hydraulic radius of the flume in centimeters, R the radius of the grain in centimeters, g the force of gravity, V_m the average velocity in centimeters, and s the slope. Using Gilbert's (1914) data, Rubey computed the effective bed velocities for the gravel sizes that have already been used for the traction curve. In addition I have computed the effective bed velocities for the sand sizes from the Vicksburg Waterways data. The results are plotted on Plate 1 and shown in Table 7.

TABLE 7.—*Critical bed velocities*

Grain diam. (millimeters)	Calc. av. bed velocities (cm. per sec.)
6.08	45.3
4.18	36.3
3.08	29.7
1.38	18.0
0.72	15.2
0.35	13.7
4.08	35.9
0.59	14.1
0.31	13.2
0.20	10.7

It should be noted that the calculated effective bed velocities for the gravels fall on the settling-velocity Curve A. Values for the sands fall to the right of the extension of Curve A. This departure may be caused by not giving sufficient weight to the effect of the film of laminar flow where small particles make up the stream bed. In addition, Hjulström (1935), and several other investigators, have shown that increased velocities are necessary to start silt and clay moving from the stream bed. This has been tentatively explained as resulting from the greater cohesiveness of such

small particles. Of course, this would require a swing to the right by the traction curve toward larger velocities. No evidence of this swing is apparent for debris as small as fine sand.

POSSIBLE APPLICATION TO SEDIMENTATION

EVALUATION OF DATA

Although the preceding discussions and data may give a fairly trustworthy picture of the competency of currents, any application to natural conditions of transportation is certain to be questionable. There seems to be no practical way of evaluating the complex and rapidly fluctuating conditions that control sedimentation, and consequently the gap between the laboratory and the field may never be satisfactorily bridged. It is with considerable hesitation, therefore, that the following suggestions on possible applications are offered.

GRAIN SIZE AND LOCAL CURRENTS

To relate properly the grain diameter of a sample to the currents that transported it, a choice must frequently be made between the average diameter, the median diameter, and the maximum diameter. If the sample is well sorted (high uniformity

TABLE 8.—*Sample 606 miles downriver from Cairo*[*]

Millimeters opening	Per cent on	Cumulative per cent through
1.65	0.0	100.0
1.17	0.1	99.9
0.83	0.0	99.9
0.59	0.1	99.8
0.42	0.1	99.7
0.30	2.2	97.5
0.21	68.9	28.6
0.10	28.4	0.2
0.07	0.1	0.1

[*] U. S. Waterways Experiment Station, Vicksburg, Mississippi (1935).

coefficient) the choice is usually not difficult. This is illustrated (Table 8) by a sample from the bed of the Mississippi River on the Head of Racetrack Tow Head, 606 miles below Cairo.

The average grain diameter is 0.23 millimeter, the median is 0.24 millimeter, and about 97 per cent of the sample is finer than 0.3 millimeter. The currents that transported this sample had a velocity of about half a mile per hour, or 25 centimeters per second, a short distance above the bed (Pl. 1). The effective bed velocity may be estimated at from 8 to 12 centimeters per second. The sample is well sorted, medium to fine sand, and probably represents the bed load at that particular spot for normal to high-water stages, but not for flood conditions. The excellence of the sorting may have been partly caused by winnowing out of the silt during low-water stages.

During floods, transportation is at a maximum, and all areas of slack water receive deposits. Sorting is usually not good because of the rapid fluctuations of both veloc-

ity and turbulence. Poor sorting may also represent the scrambling and mixing, during storms, of layers of previously well-sorted material. Incomplete sorting is illustrated (Table 9) by a sample from the bed of the Mississippi River on Head of Prairie Point Tow Head, 301 miles below Cairo. The sample is a coarse sand containing some gravel.

TABLE 9.—*Sample 301 miles downriver from Cairo**

Millimeters opening	Per cent on	Cumulative per cent through
13.33	0.0	100.0
6.68	2.5	97.5
3.33	1.7	95.8
2.36	1.2	94.6
1.65	2.1	92.5
1.17	4.3	88.2
0.83	8.1	80.1
0.59	21.1	59.0
0.42	29.4	29.6
0.30	20.1	9.5
0.21	6.1	3.4
0.10	3.1	0.3
0.07	0.2	0.1

* U. S. Waterways Experiment Station, Vicksburg, Mississippi (1935).

The average grain diameter is 0.94 millimeter, the median is 0.54 millimeter, and 2per cent of the sample is coarser than about 8 millimeters. If 8 millimeters is taken as the maximum diameter, then the currents that carried this sample had a velocity of about 2 miles per hour a short distance above the bed (Pl 1) and an effective bed velocity of about 1 mile per hour. If the average diameter of 0.94 millimeter (coarse sand) is used, none of the gravel would be accounted for. The median diameter 0.54 millimeter should not be used.

Since over 7 per cent of the sample is 2 millimeters or coarser, a more representative velocity would probably be 1 mile per hour a short distance above the bed, or about half a mile per hour for the bed velocity. The sample was probably deposited during a flood stage of the river.

GRAIN SIZE AND AVERAGE REGIONAL COMPETENCY

For many years the theory has been held that there is a progressive downstream decrease in the size of the detritus composing the bed of the Mississippi River. It was not until 1932 that a comprehensive survey of the sediments in the Mississippi River channel, by the U. S. Waterways Experiment Station, furnished sufficient data to prove this theory. Over 600 samples were taken from the channel bed at fairly uniform distances apart between Cairo and the Gulf of Mexico, during a low-water stage of the river. Table 10 has been prepared from their diagrammatic chart which shows the character of the bed materials, averaged by 25-mile reaches.

For some 500 miles downriver from Cairo abundant gravel indicates that velocities

greater than 2 miles per hour are common in the channel during high water. At normal stages, the bed load of the channel is evidently coarse to medium sand, which indicates minimum currents of about a mile per hour and effective bed velocities of a quarter of a mile or more per hour.

TABLE 10.—*Mississippi River sediments—100 to 1000 miles below Cairo*

Miles below Cairo	100	300	500	700	900	1000
Large gravel	8.0	3.0	6.0	2.0	tr	—
Medium gravel	10.0	2.0	6.0	2.0	tr	—
Fine gravel	11.0	3.0	2.0	1.0	tr	—
Coarse sand	30.0	22.0	9.0	8.0	1.0	—
Medium sand	32.0	50.0	46.0	44.0	26.0	9.0
Fine sand	8.0	18.0	26.0	40.0	68.0	65.0
Very fine sand	tr	1.0	2.0	1.0	2.0	4.0
Silt	tr	tr	2.0	1.0	2.0	10.0
Clay	tr	tr	1.0	tr	1.0	10.0

* U. S. Waterways Experiment Station, Vicksburg, Mississippi (1935).

TABLE 11.—*Average of 300 samples from Mississippi delta*

Material	Per cent
Coarse sand	tr
Medium sand	tr
Fine sand	6
Very fine sand	23
Coarse silt	30
Medium silt	16
Fine silt	7
Very fine silt	7
Clay	11

Progressive but irregular decreases in the amount of medium sand and increases in fine sand throughout the lower reaches of the river indicate a progressive average decrease in the velocity of the transporting currents. At 900 miles below Cairo the velocities should, in general, be about half as great as they are 500 miles below Cairo.

In the delta region, the active channelways are bottomed by fine sand. Most of the deposition, however, is outside the channelways in slack-water areas where detritus is dropped during high water. Most of this material is carried by the river in suspension and is composed of silt and very fine sand. This is shown in Table 11, which is an average of 300 surface and bore-hole samples taken from various places in the delta by Russell and Russell (1939). Currents of from 0.5 to 0.05 centimeter per second are sufficient to hold material of this type in suspension.

MAXIMUM DIAMETERS AND TRUE COMPETENCY

The above tentative suggestions of the relation of currents to the maximum and average diameters of particles transported are intended to emphasize minimum velocities. The actual currents may have been considerably larger. The debris that was

transported may not have been a true measure of competency simply because coarser material may not have been available. An illustration is the sample described by Lane and Kalinske (1941) that was taken from the channel of the Mississippi River at Muscatine, Iowa, during the flood of September 1938. The material was collected 0.6 foot above the river bed from a current having a velocity of 91 centimeters per second. Only 9 per cent of the sample was coarse to medium sand, and no gravel was present. With velocities of this magnitude much coarser material should have been found if the real competency of the current was effective. Obviously, coarser material was not available to the river at that particular place.

Minimum rather than maximum velocities, therefore, are usually obtained from the traction and suspension curves. This is especially so if the sample had been deposited and is not part of a load that is being transported.

SUSPENDED LOAD AND TRACTION LOAD

In some rivers the suspended load and traction load are interchangeable to a certain degree. Many rivers, however, have beds composed of sand, while the suspended load of silt and clay seldom comes to rest. In these rivers very little of the suspended load is lifted from the bed; most of it is supplied from the run-off and from tributaries. Moreover, according to Straub (1942), the actual suspended load is seldom in excess of 2 per cent, even in so-called muddy rivers.

The reason many rivers flow on beds of clean sand, although they carry in their waters countless tons of silt, is because the currents responsible for suspension are usually not competent to disturb the river bed. However, random and rapidly changing threads of velocity and turbulence, large enough to keep silt in suspension, are present in all rivers. The silt load is therefore carried efficiently and continuously in suspension.

In general, the headwaters of river systems carry a relatively large bed load, and the lower reaches a predominantly suspension load. Thus, the coarser materials, such as the gravels and coarse and medium sands, are almost always a bed load; and when relating them to current velocities the traction curve should be used. The finer materials, such as very fine sand and silt, have usually been carried into slack waters in suspension; and when relating them to current velocities the suspension curves should be used.

Eventually, much of the load of rivers reaches the ocean. The coarser materials are dropped near shore and should be considered as traction loads. The very fine sands and silts are spread far from shore by distributive currents of low velocity. Even though such currents are turbulent to some degree, it is not suggested that the major sorting, by-passing, and discontinuous deposition is accomplished from suspension. More probably bottom-creeping tractive currents have been responsible. It is suggested, therefore, that coarse silts and very fine sands should be considered as a bed load, if formed in a marine environment.

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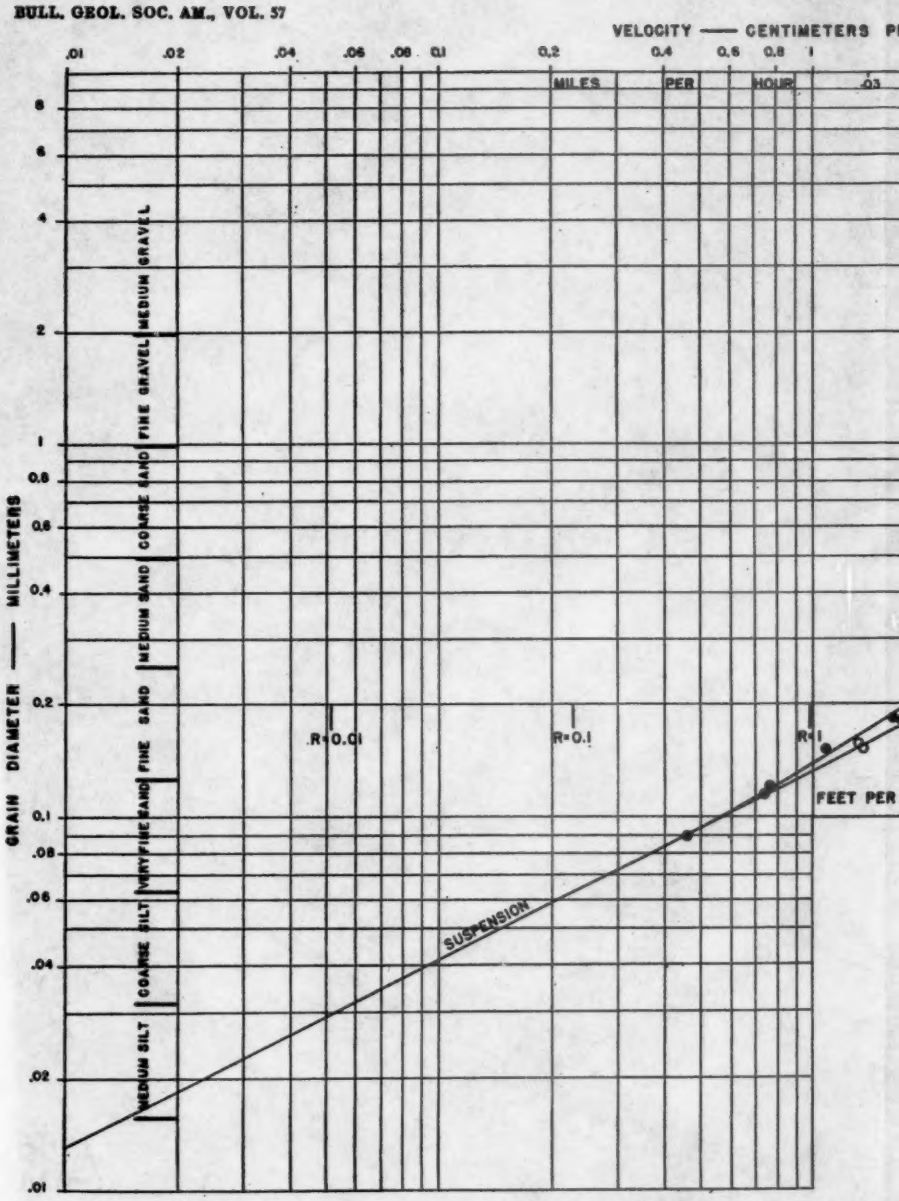

SUSPENSION AND TRACTIO

Showing the relation of grain sizes to the velocities of currents that support debris in suspension and that carry debris along the bed by traction. Curve A is based on data from smooth-sided elutriation tubes, where only the larger current velocities develop turbulence. Curve B is based on data from corrugated elutriation tubes, where even the smallest currents used develop turbulence. The traction curve is based on
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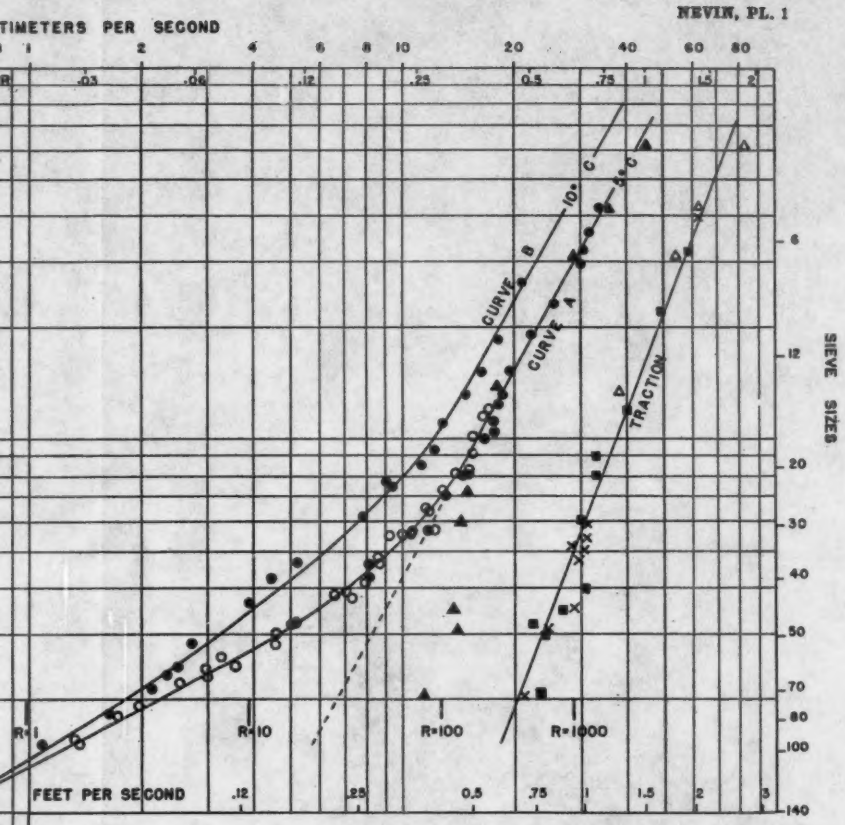

SUSPENSION AND TRACTION CURVES

- ○ DOMINANTLY LAMINAR
- ● DOMINANTLY TURBULENT
- △ GILBERT DATA
- ▲ CALCULATED BED VELOCITY
- × VICKSBURG WATERWAYS DATA
- ■ TRACTION TUBE DATA

TRACTION CURVES

based on previously published data from Gilbert's flume experiments, from the United States Waterways Experiment Station's flume experiments at Vicksburg, and on new data from traction-tube experiments. Calculated effective bed velocities, which are about 50 per cent of the current velocities a short distance above the stream bed, are also shown. The data apply to debris similar to quartz, having a density of about 2.6.

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VOL. 57, PP. 675–686, 1 FIG., 1 PL. JULY 1946

DATING SEDIMENTATION, VULCANISM, AND OROGENY IN BEARTOOTH MOUNTAIN REGION, MONTANA, BY HEAVY MINERALS

BY MARCELLUS H. STOW

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ABSTRACT

The results of this project represent a further step in the demonstration of the chronologic relationship between time and manner of mountain uplift; time of notable volcanic activity; and time of accumulation of basin-fill sediments in the Bighorn Basin and Crazy Mountain syncline regions of southeastern Montana.

The investigation indicates that the stratigraphic units traced and mapped as Hell Creek, Tullock, Lebo, and Tongue River formations from significant fossil vertebrate localities in the vicinity of Polecat Bench and Heart Mountain, Wyoming, correlate with units designated as Hell Creek, Bear, Lebo No. 1 and Lebo No. 2, and Melville, respectively, in the Crazy Mountain syncline.

A series of agglomerates along the Yellowstone River is overlain by shales and sandstones of the Hell Creek. In some areas the agglomerates truncate beds of the Claggett, Judith River, Bearpaw, and possibly the Lennep; in other areas they are interfingered with these formations. Hence they signify a predominance of volcanic activity along the northern front of the Beartooths during this time interval.

Sedimentary petrographic studies show an absence of minerals derived from metamorphic rocks, which would seem to indicate that the crystalline core of the northwestern part of the Beartooth Range had not been stripped of its cover of Paleozoic sedimentary rocks by the close of Tongue River time.

INTRODUCTION

PURPOSE OF WORK

Previous investigation (Stow, 1938) of the clastic sediments of the Lance, Fort Union, and Wasatch formations of the Bighorn Basin showed a zoning of diagnostic heavy minerals within beds whose age and sequence had already been determined on fossil evidence. Particular minerals, found to be characteristic of certain basin-fill formations, and traced to their sources in the crystalline and volcanic rocks exposed around the basin's margins, showed the times of differential uplift of the basin rims and of certain volcanic outpourings.

The present work contributes further to the petrography of Cretaceous and Paleocene sediments in the Bighorn Basin and Crazy Mountain syncline areas and to the orogenic history, conditions of sedimentation, and volcanic activity in the region.

ACKNOWLEDGMENTS

Acknowledgment is made of financial aid from the Penrose Bequest of The Geological Society of America for the expenses of the field season of 1937 and for part of the season of 1938. The writer particularly appreciates the many helpful suggestions of Professor W. T. Thom, Jr., of Princeton University, Secretary of the Yellowstone-Bighorn Research Association. Dr. Willard H. Parsons collaborated in much of the field work on the volcanics. Mr. John C. Bierer, at that time a student at Washington and Lee University, was an efficient field assistant during the progress of much of the work. Mr. Nelson C. Steenland, of the same institution, was of great help in the laboratory preparation of the sediments for microscopic study.

LOCATION OF AREA

The area under investigation is north and northeast of the Beartooth Mountains, and east of the Crazy Mountains, in south-central Montana (Fig. 1).

During the field season of 1939 and 1940, certain phases of the work were continued eastward to the type localities of the Tongue River, Hell Creek, and Tullock formations. The results of this extension of the work, however, are not yet ready for publication.

FIELD METHODS

Reconnaissance examination of the entire area and detailed study of the petrology of known vertebrate faunal zones were made at the beginning of the work in order to determine the major stratigraphy and chronology and to appraise the similarities or

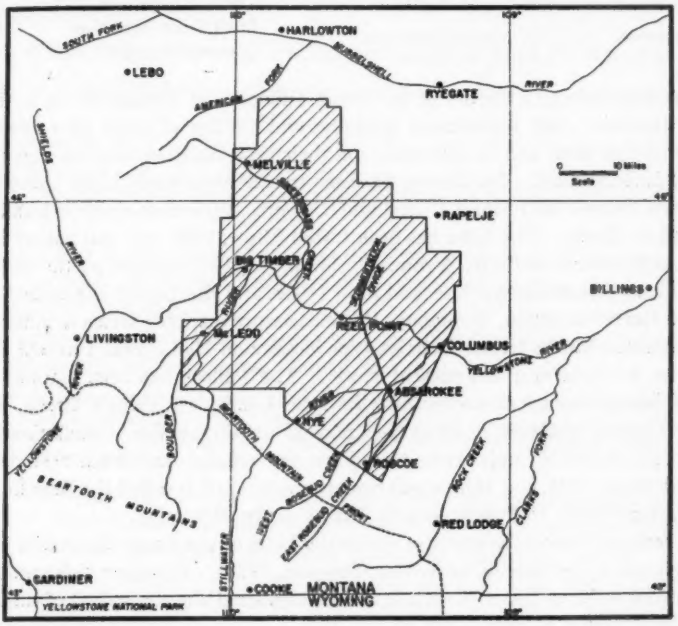

FIGURE 1.—*Sketch map of the area north of the Beartooth Mountains, Montana*

Showing location of area studied (diagonal lined area), Beartooth Mountain front (broken line), and divide between ancient Bighorn and Crazy Mountain basins of sedimentation.

differences in lithology of the stratigraphic units between the Bighorn Basin and the Crazy Mountain syncline. Contiguous areas previously mapped and described by others were critically examined.

After this preliminary view, the formations were mapped by plane table and telescopic alidade, upon bases prepared from maps of the United States Geological Survey, the Forest Service, and the Montana State Highway Department (Pl. 1).

Fresh, typical sandstone samples were collected for petrographic examination. Two or three pounds of small chips were obtained from several square yards of exposure. The localities from which these specimens were obtained are given in Plate 1.

STRATIGRAPHY

NOMENCLATURE

Following the extensive work by Dorf (1940) on type Lance and Fort Union formations and the nomenclature most recently agreed upon by the Committee on Nomen-

clature and Correlation of the North American Continental Tertiary (Wood, *et al.*, 1941), the following stratigraphic terms are used here:

Tertiary	Paleocene	Tongue River formation
		Lebo formation
		Tullock formation
Cretaceous	Upper Cretaceous	Hell Creek formation
		Lennep formation

Some may object to the use of the terms Tullock and Tongue River in the area under discussion, but preliminary mapping and tracing of units gave reasonable assurance that these can be followed from their type localities into the region of the present investigation. The Lennep has been traced by members of the United States Geological Survey and others (Stone and Calvert, 1910) from its type locality into the Bighorn Basin. The Lebo has been traced (Stow, 1938, and this paper) from its type locality nearly to Cody, Wyoming. Simpson (1937) recognized the Hell Creek in the Crazy Mountain syncline, and Stow (1938, and this paper) has traced it from there to Heart Mountain, Wyoming. Reconnaissance mapping seems to indicate that this formation can be traced from its type locality on Hell Creek, Garfield County, Montana, to the area of the present study. The Tullock has been mapped by the United States Geological Survey from its type locality on Tullock Creek, Bighorn County, Montana, almost as far as the Crazy Mountain syncline. Preliminary mapping indicates that the unit can be traced into the syncline, and it has been definitely mapped (Stow, 1938, and this paper) from there, where it is called the Bear formation by Simpson (1937), to Polecat Bench, Park County, Wyoming.

The series of massive sandstones above the Lebo of the Crazy Mountain syncline has been called the Melville formation (Simpson, 1937). However, this unit also has been traced as far as Heart Mountain and is considered the equivalent of the Tongue River formation of eastern Montana.

DESCRIPTIONS OF THE SECTIONS

Hell Creek formation.—Brown (1907) has described the Hell Creek at its type locality on Hell Creek, Garfield County, Montana. The lower member consists of fine-grained, massive, and usually cross-bedded light sepia-brown sandstones. The upper beds are less continuous and are light-blue or slate-colored clays and interbedded sandstones.

In the Bighorn Basin the formation is dominantly gray and greenish-gray shale and mudstone, weathering to clay, with thin, lenticular, yellow-brown fluviatile sandstones. It ranges from about 173 feet thick, east of Red Lodge (Stow, 1938), to about 900 feet at Roscoe, Montana (Wilson, 1936).

In the Crazy Mountain syncline, Simpson (1937) measured over 1400 feet of white, gray, greenish, and brown shales through which are distributed about 400 feet of gray sandstone.

Tullock formation.—At the type locality, this formation has been described by Rogers and Lee (1923) as follows:

"The upper member of the Lance formation—herein named Tullock member, from its exposures in the valley of Tullock Creek—is made up of yellowish sandstone and shale and contains ten more or less lenticular coal beds. Although the sandstone is lithologically similar to that in the lower part of the formation, it commonly occurs in beds less than 20 feet thick . . . much of the sandstone and shale is more or less calcareous. . . . The shale is for the most part yellowish gray to brownish, and the faint greenish tint so characteristic of the shale in the lower part of the Lance is very uncommon. Many bands of carbonaceous shale are present in the Tullock member, and these also help to give it a brownish-yellow cast."

East of Red Lodge, Montana, the Tullock comprises about 450 feet of an

"alternation of massively bedded, buff-to-white, moderately persistent sandstones and gray mudstones" (Wilson, 1938).

and at Roscoe it is

"irregularly bedded, uniformly persistent, medium-grained, white and yellow sandstone with streaks of coal, interbedded with gray and olive-green mudstone, yellow sandy shale, and brown carbonaceous shale, about 350 feet thick" (Wilson, 1936).

In the region of the Crazy Mountains the Tullock (or Bear, of Simpson, 1937) is mainly gray platy sandstones, 1 to 3 feet thick, with shale partings (Simpson, 1937), and aggregating about 600 feet in thickness.

Lebo formation.—This formation was first described by Stone and Calvert (1910, p. 753) on Lebo Creek, Sweetgrass County, Montana. . . .

"the Lebo member is composed largely of gray, red, green, brown, and dark shale, and chocolate-colored sandstone, while in T. 6N., R. 16E., it is characterized as chocolate-colored, although the individual members are for the most part dark greenish and brown sandstones and shales with little or no light-colored beds."

Near Red Lodge the Lebo is represented by about 3500 feet of somber, olive-gray, black, and purplish shale and mudstone weathering to clay, interbedded with carbonaceous shales and thin, gray, fresh-water limestones, weathering brown.

Simpson (1937) described the Lebo, somewhat modified after Stanton and Silberling (Stanton, 1909). The formation is divided into Lebo no. 1 (lower), and Lebo no. 2 (upper). The whole formation is represented by about 1300 feet of grayish-green somber shades and interbedded gray, brown, and grayish-green sandstones. Some thin beds of gray limestone weather brown.

Tongue River formation.—Taff (1909) used the term "Tongue River Coal Group," and in 1924 Thom and Dobbin described the Tongue River member of the Fort Union formation as

". . . yellow or light-colored strata containing massive sandstones and numerous thick coal beds. The top of the member is placed beneath bed K of Sidney field, bed F of Sentinal Butte field, and Roland Coal of Sheridan field. The base is placed beneath the light-colored coal-bearing rocks which characteristically form a marked clinker-capped escarpment rising above lowlands or badlands developed from the somber Lebo shale, with which it intertongues at the contact."

In the Red Lodge area there is about 4000 feet of massive, cross-bedded sandstones (many of which are white when fresh but weather to yellow brown) interbedded with gray shale and numerous carbonaceous layers, including some thick beds of coal. Yellow, argillaceous, fresh-water limestones are common.

This formation in the Crazy Mountain region is likewise over 4000 feet thick and consists of massive yellowish sandstones and interbedded gray and yellowish shales. A prominent massive basal sandstone is a conspicuous horizon marker. A few thin lenses of coal are present.

MINERALOGY

PREPARATION OF SAMPLES

The sandstone samples were prepared for mineralogic study by the standard methods of sedimentary petrography using bromoform. Although quantitative beterminations were not made, approximately equal amounts of sediment were used throughout the various procedures.

CLASSIFICATION OF DATA

Mineral ratios were not determined on a percentage basis by grain counts, but for purposes of comparison the commonly used terms flood, abundant, common, and rare were applied by estimation. This more rapid method seemed to be sufficiently accurate.

HEAVY MINERALS

Opaque.—The opaque minerals were of minor importance and were not studied in detail. Those identified were hematite, ilmenite, leucoxene, limonite, magnetite, and pyrite. As limonite was dissolved by hydrochloric acid at the beginning of the laboratory treatment of the sample, its occurrence was given no further consideration. Ilmenite and leucoxene were by far the most common of the other opaque minerals.

Nonopaque.—The following nonopaque minerals were identified, and a few significant comments on each are added.

ANATASE was recognized in only one sample and was represented by only two euhedral grains.

APATITE was identified in about one fourth of the slides, in spite of the treatment with acid.

AUGITE was present as angular yellowish-green grains in some samples of Hell Creek, Tullock, and Lebo formations but was absent from the Tongue River. It is of considerable significance and will be discussed more fully.

BIOTITE, or closely related minerals, were found in most of the samples.

CARBONATES were removed by preliminary acid treatment.

CHLORITE is present in nearly all the samples and occurs in various shades of blue green andyellow green. No particular significance could be attached to it.

GARNET is usually colorless or pale pink. A few samples carry a deep reddish-brown variety.

HORNBLENDE is rarely observed. Splintery green grains were identified in about one third of the Lebo samples but not elsewhere.

MUSCOVITE was identified in almost all samples.

RUTILE is represented by rounded red or yellow grains in most of the samples.

SPHENE occurs sporadically in several slides from all formations except the Tongue River. It is euhedral and probably authigenic.

TOURMALINE was observed in essentially all specimens as euhedral prisms and anhedral rounded grains. Various shades of brown, blue, purple, green, and yellow were found.

ZIRCON is ubiquitous; it ranges from rare to flood but was usually common. Euhedral grains and rounded ones are present, both usually colorless, but a few purple ones were found.

ZOISITE was identified in one sample of Tullock and several samples of Lebo sandstone. In all cases its frequency was rare.

LIGHT MINERALS

Quartz, several feldspars, and chert were present, but were not specially studied. Doubtless detailed examination would yield information of value.

MINERAL CONTENT OF THE FORMATIONS

Table 1 shows the relative persistence and frequency of certain significant minerals in the four formations determined from many samples from each formation in the area west of a line from Roscoe to Reed Point (sedimentation divide) (Pl. I). Table

TABLE 1.—*Relative frequency and persistence of significant minerals west of sedimentation divide*

	Garnet colorless	Garnet red	Zircon	Tourmaline	Biotite	Muscovite	Chlorite	Rutile	Augite	Hornblende	Epidote	Staurolite
Tongue River.....	Ca	d	Ca	Ra	Aa	Ca	Ca	Rb	d	d	d	d
Lebo.....	Ca	Rc	Ca	Rb	Rc	Rc	Cc	d	Ca	Rb	d	d
Tullock.....	Rb	Rc	Ca	Ra	Cb	Ca	Ca	Ra	Cc	d	d	d
Hell Creek.....	Rb	d	Ca	Ra	Cb	Cb	Cb	Rb	Cb	d	d	d

Frequency:
A = abundant
C = common
R = rare

Persistence:
a = present in 100% of the samples
b = present in approximately 80% of the samples
c = present in approximately 10% of the samples
d = absent from all samples

TABLE 2.—*Relative frequency and persistence of significant minerals east of sedimentation divide*

	Garnet colorless	Garnet red	Zircon	Tourmaline	Biotite	Muscovite	Chlorite	Rutile	Augite	Hornblende	Epidote	Staurolite
Tongue River.....	Ca	Cb	Ca	Cb	Rb	Rb	Rb	Rb	d	d	d	Rb
Lebo.....	Ca	Rc	Ca	Ca	Rb	Cc	Cb	d	d	d	Rb	d
Tullock.....	Aa	Rb	Ca	Ca	Rb	Ca	Ca	Ra	d	d	Rb	Rc
Hell Creek.....	Rb	d	Ca	Ca	Rb	Rb	Ca	Rb	d	d	Rb	d

Frequency:
A = abundant
C = common
R = rare

Persistence:
a = present in 100% of the samples
b = present in approximately 80% of the samples
c = present in approximately 10% of the samples
d = absent from all samples

2 is a similar diagram for the formations east of the Roscoe-Reed Point line (sedimentation divide).

The tables show significant differences. In the Hell Creek beds east of the Roscoe-Reed Point line, colorless garnet is present in most samples but is rare in frequency; red garnet is not found; zircon is present in all samples and is common; tourmaline is present in all samples and is also common; biotite is present in most samples and is rare; muscovite appears in most samples but is common; rutile, present in most samples is rare; chlorite, present in all samples, is common; augite, hornblende, and staurolite are not present; epidote, although present in most samples, is rare. In contrast, west of the Roscoe-Reed Point line, the Hell Creek sediments, while differing slightly in minor points, differ significantly in that epidote is absent but augite occurs in appreciable amounts in most of the samples examined.

In the Tullock sediments the differences between the two areas are even more striking. East of the line colorless garnet is present in all samples and is abundant, and

the red variety is present in most samples but is rare. West of the line the colorless garnet is present in most samples but is rare, and the red variety is found in only an occasional sample and likewise is rare. The relationships among zircon, tourmaline, biotite, muscovite, chlorite, and rutile in the two areas are so close that the slight differences are insignificant. However, important differences are the presence of augite in the western sediments and its absence from the eastern ones, and the occurrence of epidote and staurolite in the eastern sediments and their absence from the western.

Likewise, there are notable differences in the Lebo sediments from the two areas. Most important of these are the universal presence of augite in common amount and of hornblende in rare amount in the samples west of the Roscoe-Reed Point line, in contrast with their absence east of the line. Also, epidote is present in the east and absent in the west.

Lastly, there are contrasts between the sediments of the Tongue River in the two areas. Particular attention is directed to the persistence and frequency of the red garnet in the eastern area and its absence from the western. Slight, and presumably unimportant, differences exist in the persistence or frequency of tourmaline, biotite, muscovite, and chlorite. No augite, hornblende, or epidote is found in either area. Staurolite, present but rare in most of the eastern samples, is absent from the western.

SOURCES OF SEDIMENTS

This investigation reveals that west of a line between Roscoe and Reed Point (Pl. 1), no minerals of direct metamorphic-rock derivation are present in Hell Creek, Tullock, Lebo, or Tongue River formations, whereas to the east of this line there are minerals derived from metamorphic rock types. South of Red Lodge, kyanite and large amounts of epidote and staurolite are present in these formations.

The augite, hornblende, and some other minerals found in the sediments of the western area have been traced to a provenance of volcanic agglomerates between the Yellowstone River on the north and the Beartooth Mountains on the south and between the Boulder River on the west and Bridger Creek on the east. The origin and structure of these Deer Creek igneous rocks have been described by Parsons (1942) who has described (personal communication) the petrography of these rocks, in part, as follows:

> "The Enos intrusives and breccias (local in extent but slightly older than the others) contain phenocrysts of biotite, green euhedral pleochroic hornblende, tiny magnetite grains, tiny apatite needles, and large crystals of andesine. The groundmass is badly altered to kaolin, etc. The younger breccias and various dikes and pipes are mostly andesites, some hornblende, some augite andesites. These are mixed together in the breccias with some dacite fragments, a few basaltic fragments, etc. Green pleochroic hornblende with the typical hornblende cleavage is the commonest, followed by pale gray-green euhedral (8-sided) augite with 2-direction cleavage in the smaller crystals. These rocks carry the usual magnetite, tiny apatite crystals, and feldspars. In the breccias, the femags are often more or less altered to chlorite, fine-grained and pleochroic."

Much of the zircon, tourmaline, and rutile is derived from pre-existing sedimentary formations. The garnet cannot be traced readily to a definite source, but indications suggest that most of it is at least second-cycle.

AGE RELATIONS OF VOLCANICS

The volcanic agglomerates along the Yellowstone River are overlain by shales and sandstones of the Hell Creek. Along the East Boulder River the agglomerates truncate beds of Eagle, Claggett, and Judith River age. To the east, on the Stillwater River, the agglomerates lie, with angular unconformity, on beds of the Claggett, Judith River, and Bearpaw formations. Wilson (1936) describes agglomerates on the Stillwater that can be "traced laterally into andesitic and tuffaceous beds actually interbedded with strata of Judith River age."

These relationships presuppose more or less continuous volcanic activity in the region from Judith River to at least Lennep time.

BEARING OF MINERAL EVIDENCE ON THE BASIN FILL

The pre-Cambrian core of the Beartooth Mountains has been thrust up eastward and northeastward at low angles along their eastern front. This movement steeply folded and fractured the cover of Paleozoic sediments. Along the north front the movement was appreciably less, and the Paleozoic sediments were not so sharply draped nor fractured.

The petrographic data derived from the basin-fill sediments demonstrate that where uplift and fracturing of the Paleozoic cover was most intense subsequent denudation was most effective and the mountain core was exposed earliest. The appearance of detritus derived from crystalline rocks was first noted in sediments of Tullock age along the east front of the Beartooth Range. On the north front, where the Paleozoics appear as a long dip slope to the north, and consequently fracturing was at a minimum, these rocks were more resistant to subsequent denudation than those on the strongly faulted east front. Also, the volcanics already discussed probably lapped onto the Paleozoic rocks of the region. This would have a two-fold effect: it would increase the amount of cover on the crystalline core and decrease the gradient of streams flowing from the area of uplift. Both these factors would tend to lengthen the time required to expose the crystalline core and offer an important source of sediment for distribution to the north.

The absence of material of metamorphic or intrusive igneous rock types form the Hell Creek, Tullock, Lebo, and lower Tongue River sediments indicates that detritus from the mountain core was not available until after early Tongue River time. Sedimentary formations and volcanic rocks were supplying the sediment to the depositional area to the north until this time.

From the region of Heart Mountain and Polecat Bench, Park County, Wyoming, northward and northwestward to the Crazy Mountains, the characteristic lithology of each of the formational units of Hell Creek, Tullock, Lebo, and Tongue River is distinct and mappable. This suggests that, in general, conditions of sedimentation were essentially similar throughout the entire area during the time represented by each of the formations. However, mineralogic data indicate that although there was an extensive basin of deposition to the east, northeast, and north of the Beartooth Range there were at the same time at least two distinct areas into which there was no deposition of sediment common to both areas. This is demonstrated by the strik-

ingly different mineral assemblages east of and west of a line between Roscoe and Reed Point (Pl. 1). This line strikes approximately north from near the northeast corner of the Beartooth Mountain uplift and represents the position of a structural "high" between the Crazy Mountain syncline to the west and a northward extension of the Bighorn Basin on the east. Thus there is evidence of a low divide partially separating two basins, one to the west in which was deposited sediment derived from pre-existing sedimentary and volcanic rocks, and the other to the east which was receiving sediment from erosion of metamorphic and intrusive igneous rocks (probably located in the east and central part of the Beartooths) as well as from sedimentary formations. The initiation of depositional areas as early as Hell Creek time corresponding to the present Crazy Mountain syncline and the northward extension of the Bighorn Basin is likewise indicated.

CONCLUSIONS

The results of this project lead to the following conclusions:

(1) The lithology of the Hell Creek, Tullock, Lebo, and Tongue River formations is so distinctive that they can be traced continuously from the region of Heart Mountain and Polecat Bench, Park County, Wyoming, along the west side of the Bighorn Basin, around the northeast front of the Beartooth uplift, and into the Crazy Mountain syncline. This continuity of characteristic lithology is due to deposition under essentially the same conditions throughout the region during any given time interval.

(2) As early as Hell Creek time two depositional basins had been established. These corresponded to the present area of the Crazy Mountain syncline and the northward extension of the Bighorn Basin.

(3) Detailed mineralogic studies show that the deposits in the western basin were not derived from the same rock types as were those of the eastern area.

(4) The crystalline core of the area of mountain uplift was exposed to denudation earlier where thrusting was most intense and considerably later where Paleozoic formations were not extensively deformed and where appreciable volcanic material had accumulated.

(5) Volcanic activity in the area along the present north front of the Beartooth Range was more or less continuous from at least Judith River into Lennep time.

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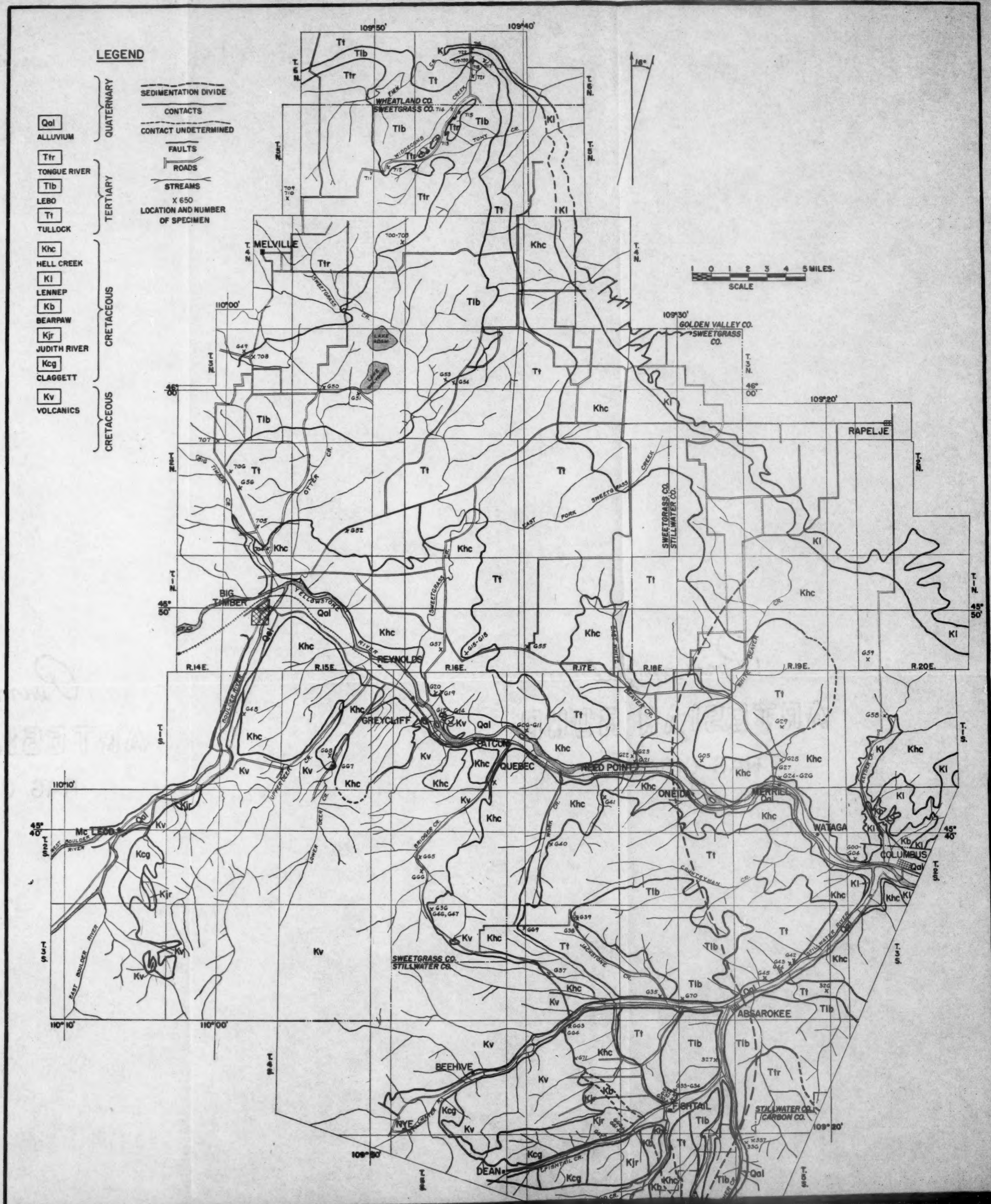
LEGEND
QUATERNARY
Qal ALLUVIUM
TERTIARY
Ttr TONGUE RIVER
Tlb LEBO
Tt TULLOCK
CRETACEOUS
Khc HELL CREEK
Kl LENNEP
Kb BEARPAW
Kjr JUDITH RIVER
Kcg CLAGGETT
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REYNOLDS
GREYCLIFF
McLEOD
BEEHIVE
NYE
DEAN
FISHTAIL
ABSAROKEE
COLUMBUS
WATAGA
ONEIDA
REED POINT
PATCON
QUEBEC
RAPELJE
WHEATLAND CO.
SWEETGRASS CO.
GOLDEN VALLEY CO.
SWEETGRASS CO.
SWEETGRASS CO.
STILLWATER CO.
STILLWATER CO.
CARBON CO.
YELLOWSTONE RIVER
BOULDER RIVER
WEST BOULDER RIVER
EAST BOULDER RIVER
SWEETGRASS CREEK
OTTER CR.
DEER CR.
BRIDGER CR.
REEDER CR.
COUNTRYMAN CR.
JACKSTONE CR.
STILLWATER RIVER
EAST FORK SWEETG PASS CREEK
BEAVER CR.
WHITE BEAVER CR.
SPRING CR.
SPRING TIMBER CR.
LAKE ADAM
R.14E.
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R.18E.
R.19E.
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T.6 N.
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T.1 S.
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T.5 S.

GEOLOGIC MAP FROM FISH CREEK, WHEATLAND COUNTY, TO ROSCOE, CARBON COUNTY, MONTANA

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CAMBRIAN AND EARLY ORDOVICIAN STRATIGRAPHY OF THE LOWER ST. LAWRENCE VALLEY

BY FRANCO RASETTI

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ABSTRACT

This paper deals with the stratigraphy of the rocks generally known as the "Sillery formation", chiefly exposed on the south shore of the St. Lawrence below Quebec City. It is shown that paleontologic evidence requires revision of the common belief that these rocks represent a single series of strata of early Canadian age. The fossils indicate that some of the strata are Lower Cambrian, while others are undoubtedly Canadian. A detailed study of significant sections in the Lévis-Chaudière area enables the writer to present a new interpretation of the stratigraphy.

The lower Cambrian appears to be represented by more than 2000 feet of shale and sandstone; a few fossils occur in the upper portion of the series. For this complex the writer proposes the new name, Charny formation, discarding the old name, "Sillery", whose continued use would cause confusion. A characteristic conglomerate, here named the Ville Guay conglomerate, overlies the Lower Cambrian with-

out apparent unconformity. Almost certainly the Middle Cambrian is not represented in the area, and probably the Upper Cambrian is also absent. Hence the Ville Guay conglomerate is considered as basal Ordovician. There follows a succession of shales with interbedded sandstones, probably about 2000 feet in thickness. These strata yield a few fossils that appear to indicate an early Canadian age, and they are designated as the Lauzon formation, a name already employed by Logan The Lauzon grades upward into the Lévis shale without any sharp limit.

It is shown that most of the strata outcropping east of the Lévis-Chaudière area for over 250 miles are of Canadian age and can be referred, at least tentatively, to the Lauzon formation.

INTRODUCTION

This paper is an attempt toward a better understanding of the stratigraphy of the early Paleozoic rocks generally known as the "Sillery formation". Notwithstanding the work of such eminent geologists and paleontologists as Logan, Billings, Ells, and Walcott, the age of these rocks is still questionable. The writer has been studying the area for several years, mainly for the purpose of collecting fossils from the numerous outcrops of conglomerate occurring in these strata. Fossils in place, however, are extremely scarce, and this is the main reason for the present uncertainty about the stratigraphic position of the "Sillery". In 1943, the writer's persistent search for fossils in these rocks was rewarded with the finding of a small Lower Cambrian fauna in place (Rasetti, 1945a). This find showed more clearly than ever before that the generally accepted views on the age of the "Sillery" required revision. In 1945, the writer decided to undertake this work, and for this purpose examined the south shore of the St. Lawrence, devoting particular attention to the outcrops where the strata appeared less disturbed and hence more promising for the understanding of the stratigraphy. The most significant sections were carefully searched for fossils, and some yielded valuable information.

The writer believes that an advance has been made in this complex problem.

The writer is greatly indebted to The Geological Society of America for a grant from the Penrose Bequest that enabled him to carry out the field work in 1945.

SUMMARY OF PREVIOUS WORK

Logan was the first to attempt a systematic investigation of the rocks that are the object of this study; indeed, he used them to establish his "Quebec group". It is not the writer's intention to review the history of the problems connected with this name, and the related "Taconic question". It will be necessary, however, to recall how the terms employed for describing these rocks were originally defined and how, sometimes, their content was gradually modified until they came to signify something very different from their original meaning.

In the *Geology of Canada*, Logan (1863) established the type section of the principal portion of the "Quebec group" on the southern coast of the Island of Orléans. There he believed 5025 feet of strata were represented, although he mentioned (Logan, 1863, p. 227) that:

"the beds are, however, in some places so corrugated and broken that the measurements here given can only be taken as rude approximations to the truth."

These strata consist mostly of shale, with some sandstone and conglomerate; they include the graptolite-bearing shales that are so well represented at Lévis. The whole series was styled by Logan as the "Lévis formation".

On the north shore of the St. Lawrence, Logan observed a series of sandstones and red shales, exposed between Sillery and Cap Rouge and whose thickness he estimated at 2000 feet. These strata he designated the "Sillery formation". He, moreover, assumed that these rocks should be placed above the Lévis, as exposed on the Island of Orléans, thus giving a total thickness of 7000 feet for this composite section of the "Quebec group".

Later work by Logan and his collaborators consists mainly in the rather tentative assignment of rocks outcropping in other areas to the different members of the "Quebec group" as defined in the type section, and need not concern us here. However, it must be mentioned that part of the Lévis formation was separated under the name "Lauzon" (Richardson, 1866), and still later the "Lauzon" was added to the "Sillery". The name Lévis was restricted to some 1200 feet of graptolite-bearing shales outcropping at Lévis, and the "Sillery", including the former "Lauzon", extended to all the rest. This is the nomenclature that has generally been used up to the present day.

Richardson (1870) gave a different interpretation of the stratigraphy of the area. The rocks that Logan had included in the "Quebec group" were separated into "Potsdam" (Cambrian) and "Quebec group" (early Ordovician). Within each of the two series Richardson recognized three divisions which, for the "Quebec group", were those established by Logan. Richardson's conclusions were founded on insufficient and misinterpreted paleontologic evidence and have not been accepted by later workers; nevertheless, the attempt is noteworthy because Richardson appears to have been the first to realize the heterogeneous nature of the strata known as "Sillery" and "Lauzon".

The next important step in the study of the problem was accomplished by Ells. In two papers Ells (1889; 1892) gave an excellent review of all previous work, and reached new conclusions that were endorsed by Walcott (1890) and, with minor modifications, have been accepted to this day.

Ells' results showed that so many heterogeneous rocks had been lumped in the "Quebec group" that it now contained strata ranging in age from pre-Cambrian to Upper Ordovician. Hence he proposed that the name be abandoned. As to the original, restricted "Quebec group", consisting of Lévis and "Sillery", Ells showed, mainly on the evidence of the graptolites studied by Lapworth, that the order of the strata as given by Logan was inverted—*i.e.*, that the "Sillery" was older than the Lévis. Ells regarded the "Sillery" as Upper Cambrian and the Lévis as Lower Ordovician.

After Ells, Dresser (1912) attempted to subdivide the "Sillery", at least in part of its outcrop area. Young (1913), Raymond (1913), and Clark (1924) contributed various observations, partly of a paleontologic character, tending to show that there is no sharp limit between "Sillery" and Lévis but that the "Sillery" grades upward into the Lévis. These conclusions have spread the almost generally accepted belief that the whole of the "Sillery" and Lévis is Lower Ordovician.

Recently discovered facts show that the above conclusion is unwarranted. Ulrich and Cooper (1938), in their revision of the Ozarkian and Canadian Brachiopoda, restudied that often-quoted fossil, the *"Obolella" pretiosa* of Billings, the only significant species ever found in the "Sillery" at the type locality. They concluded that this form definitely belongs to the genus *Botsfordia*, which is typically Lower Cambrian. More recently, the writer (Rasetti, 1945a) found the first trilobites in place in rocks hitherto assigned to the "Sillery", a few miles east of Lévis. The fauna includes *Bonnia* and is unquestionably Lower Cambrian. This paleontologic evidence leaves no doubt that portions of what has been called "Sillery" are Lower Cambrian. It is equally certain, on the evidence of graptolites, that other portions of the "Sillery" are of early Ordovician age.

The purpose of this work is to divide the "Sillery" into its Cambrian and Ordovician portions and to establish the corresponding formations.

AREAL EXTENT, STRUCTURE, AND LITHOLOGY OF THE "SILLERY"

The rocks that form the object of this study are chiefly exposed along a narrow band on the south shore of the St. Lawrence, beginning at a point 12 miles above Lévis, where they are thrust over strata of Cincinnatian age. South of the river they certainly extend for a considerable, but not accurately determined, distance farther west. The various authors differ greatly in the limit that they assign to the "Sillery" to the east. Ells (1892) would include in the "Sillery" all the rocks (excluding limited outliers of younger strata) that outcrop on the shore as far as the tip of the Gaspe peninsula, where they are faulted against the Devonian. Most of the recent authors restrict the name to the strata west of a point somewhere between Matane and Cap Chat. There is very little doubt that all the rocks exposed on the Gaspe shore from Cap Chat to Cap des Rosiers (at the contact with the Devonian) are either Lower or Middle Ordovician. This is proved by the evidence of graptolites collected at several places (Lapworth, 1887; Ells, 1892; Jones, 1934). Since our problem is to determine what portion of the "Sillery" is Cambrian, this eastern area will not be considered. Furthermore, most of the present work deals only with the westernmost portion of the remaining area—*i.e.*, the vicinity of Lévis and the Chaudière river—since this area is believed to present the most important stratigraphic problems.

The general structure of the area is conditioned by the great Taconic overthrust. The strata in question occur in a thrust sheet that was pushed from the southeast, and hence their present position is considerably northwest of the original place of sedimentation. In the process the strata were strongly folded, and numerous faults of various importance were developed within the thrust sheet. Consequently, the sediments are greatly disturbed, and it is difficult to find a section showing a considerable thickness of beds in clearly recognizable order. Moreover, since the axes of the folds generally parallel the river, good sections on the shore are rare. This makes the study of the stratigraphy particularly difficult, since extensive exposures are largely limited to the shore of the St. Lawrence.

Other factors add difficulty to the stratigraphic problem. Fossils in place, as already mentioned, are extremely scarce, chiefly because of the excessive shallowness

of the waters in which the sediments were deposited. Another factor that has contributed to the existing confusion is the great lateral variation in the lithology of the sediments, even within short distances. Almost everywhere in the area the hard beds of sandstone, quartzite, and limestone conglomerate are lenticular, and thick deposits of this type thin out and disappear within short distances. Hence they can hardly be used for correlation on a lithologic basis. Conversely, strata of almost identical lithologic character, for example red shales, undoubtedly occur at widely different horizons. All the earlier workers seem to have greatly underestimated the complications arising from these circumstances since they attempted correlation of beds at distances of hundreds of miles on lithologic criteria.

Probably over 90 per cent of the rocks in question are shale, although the harder beds are often conspicuous because they more easily form outcrops. The lithology of the strata has been often described (Logan, 1863; Bailey and McInnes, 1893; Dresser, 1912), and little need be said about them. They are mostly red or green shales, often the two alternating in layers of varying thickness. Beds of sandstone, mostly from an inch to 1–2 feet in thickness, frequently alternate with the shale. Limestone forms a much rarer component of the sediments, but nevertheless thin limestone beds do occur at some horizons in most of the area. Black shale represents only a local development of very limited extent, such as for example at Lévis.

More information on the character of the sediments will be given in the detailed discussion of localities.

DESCRIPTION OF LOCALITIES AND SECTIONS IN THE LÉVIS-CHAUDIÈRE AREA

INTRODUCTORY STATEMENT

A detailed examination of the outcrops and a perusal of the literature showed that earlier students had often made a poor choice of the sections that they used as a basis for discussing the local stratigraphy. Thus, at the original section of the "Sillery" of Logan, between Sillery and Cap Rouge, the strata are so broken by faults that it is almost impossible to ascertain their thickness and to determine the relative ages of the beds. Much the same can be said for the supposed 5025 feet of strata of the Lévis, said by Logan (1863) to occur on the south shore of the Island of Orléans. The beds are much folded and faulted, and the writer believes that what Logan considered the bottom and top portions of this "Lévis" are Ordovician, while his middle portion is believed to be Lower Cambrian.

Therefore, the writer carefully searched chiefly on the shore of the St. Lawrence, for sections where considerable thicknesses of strata occur in recognizable order; and, moreover, where fossils give at least some indication of the age of the beds. The localities where the most significant sections were observed are described.

CHAUDIERE FALLS SECTION

Strata that lithology and fossil content show to be equivalent to Logan's typical "Sillery" are well exposed at the falls of the Chaudière River, near the village of Charny (Fig. 1). The best exposures are on the eastern bank of the river and extend

from the top of the falls downstream. The strike of the beds is E.–W. (magnetic), and the dip 35°–40° S. For a thickness of over 1500 feet the strata maintain an almost constant strike and dip, and the succession can be worked out without ambiguity. The strata were measured for about a quarter of a mile below the falls; farther downstream a sharp overturned anticline causes repetition of the preceding beds (Fig. 2; Pl. 1).

The section in descending order is the following.

	Thickness of unit	Thickness to base of section
	Feet	
14. Green or dark-gray, rarely black, fine-grained shale, cleaving readily along the bedding (*Botsfordia pretiosa* shale). *Botsfordia pretiosa* common throughout	78+	1517
13. Sandstone ledge, forming lip of falls	6	1439
12. Red shale, with thin layers of green shale, and thin beds of sandstone in the top and bottom portions. The thickness of the upper part had to be estimated as the beds are exposed in the vertical cliff	650	1433
11. Alternating beds of shale and sandstone	35	783
10. Coarse, heavy-bedded sandstone	20	748
9. Alternating beds of shale and sandstone	32	728
8. Coarse sandstone; the upper surface of these beds forms escarpment	23	696
7. Red shale, with standstone beds, especially in upper portion	105	673
6. Heavy-bedded sandstone	17	568
5. Alternating beds of shale and sandstone	34	551
4. Heavy-bedded sandstone	17	517
3. Alternating beds of shale and sandstone	24	500
2. Heavy-bedded sandstone	26	476
1. Mostly red shale, with layers of green shale, and sandstone beds, especially near the base; small faults make the measurement of the thickness somewhat approximative	450	450

Both the top and bottom of the formation are concealed. Farther downstream sandstones thicker than any of those described above occur, which makes it likely that still lower beds are represented; however, the strata are too disturbed to permit determination of their succession. The coarse sandstones are the typical "Sillery sandstone" of Logan. The *Botsfordia pretiosa* shale is identical in lithology and fossil content with that occurring at Sillery and at the bridge of the Canadian National Railways on the Chaudière, less than a mile upstream from the falls. The latter locality is the type locality for *Botsfordia pretiosa* (Billings) and *Lingulella ella* Walcott. It is fortunate that the guide fossil of the "Sillery" can be found at a definite horizon in the Chaudière falls section, since at the typical locality there is only an isolated outcrop of the shale.

The name *Botsfordia pretiosa* shale was proposed by the writer (Rasetti, 1945a) as it appeared convenient to designate by a special term a member of the "Sillery" well characterized by its lithology and fossil content. As a matter of fact, *Botsfordia pretiosa* was found only in shale of this type; and, conversely, wherever shale of this precise lithology occurs, it invariably yielded its characteristic fossil. The shale can

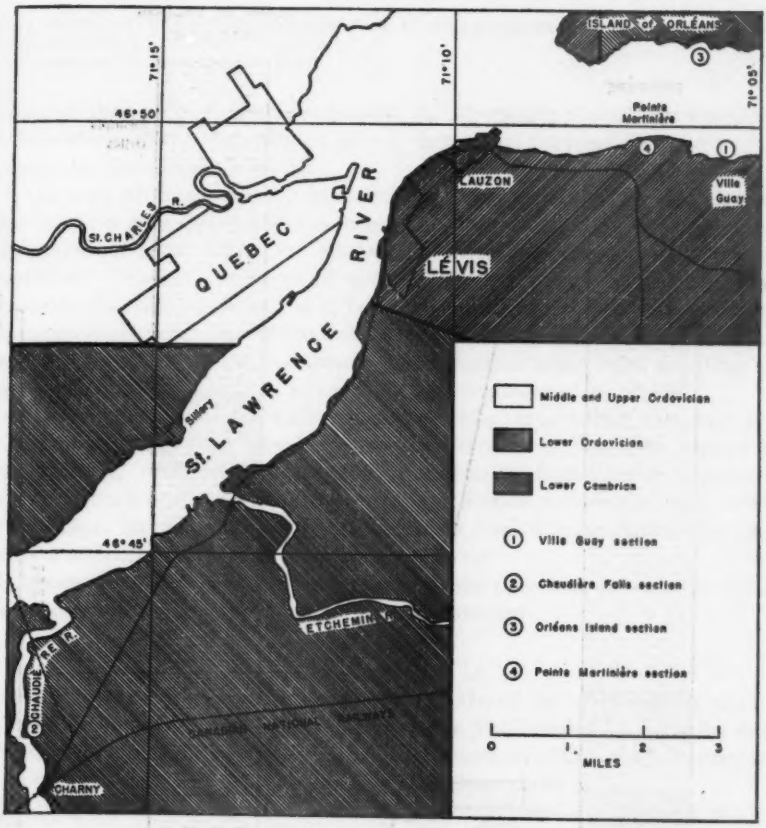

FIGURE 1.—*Geological map of the Lévis-Chaudière area, showing location of sections*
Heavy lines indicate some of the most important faults.

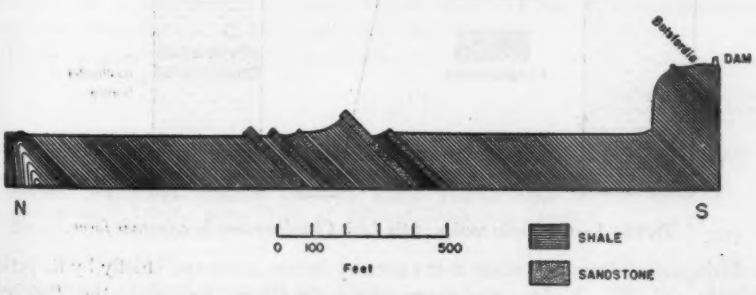

FIGURE 2.—*Chaudière falls section*

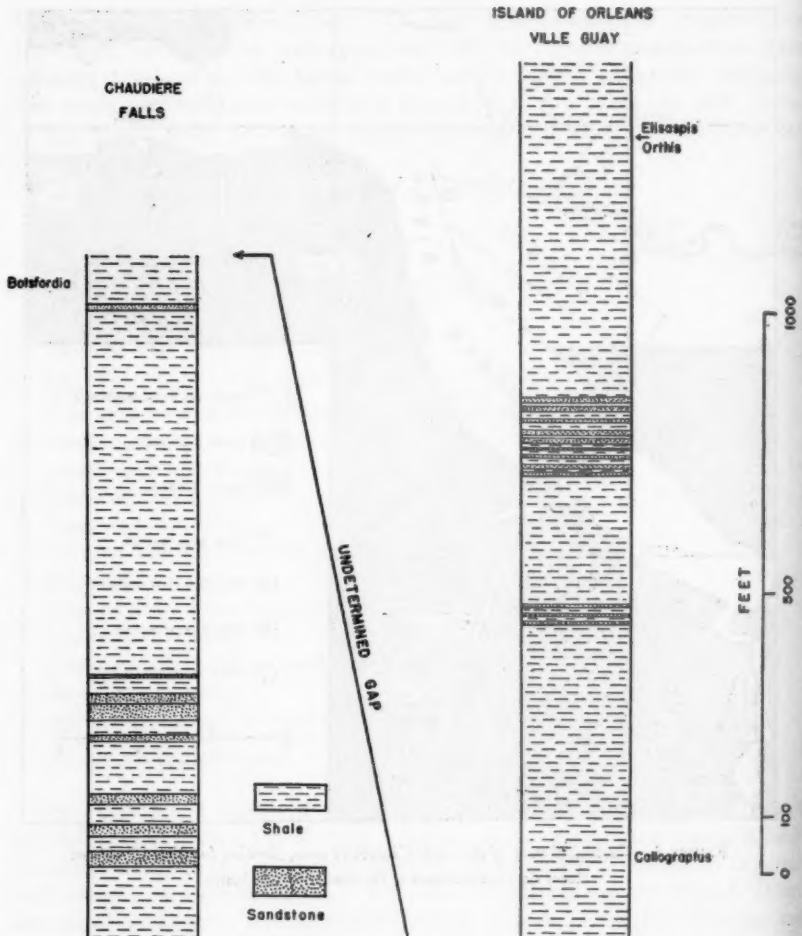

FIGURE 3.—*Composite section of the Lévis-Chaudière area in columnar form*

be distinguished from any other in the area by its fine grain and chiefly by its perfect cleavage (Pl. 1). Besides the three above-mentioned localities, the *Botsfordia pretiosa* shale was found at:

(1), road cut on the new Quebec-Montreal road, 3.0 miles southwest of the Quebec bridge.
(2), river cliff, 2.0 miles south of Lévis.
(3), road cut, 3.0 miles east of St. Vallier.

None of these outcrops supply any additional information about the stratigraphic position of the shale. In particular, none of them afford the possibility of extending upward the Chaudière falls section.

A thorough but fruitless search for further significant fossils was made at all localities where the *Botsfordia pretiosa* shale occurs. This was done especially in view of Ells' statement (Ells, 1889) that *Botsfordia pretiosa* occurs associated with Lévis graptolites. This fact, if true, would of course disprove Ulrich and Cooper's (1938) contention that this brachiopod is of Lower Cambrian age. A particularly careful search was made in the beds of black shale, as more likely to yield graptolites, but no trace of these fossils could be found. Impressions of algae were sometime observed, which might have been mistaken for poorly preserved graptolites.

On the other hand, the writer suspects that brachiopods occurring with graptolites in Ordovician shales may have been wrongly identified as *Botsfordia pretiosa* by earlier workers. This certainly happened for an *Acrotreta* from black shale at Métis, which has been recently described by Howell as *Acrotreta metisensis* (Howell, 1944). In conclusion, the writer has never seen *Botsfordia pretiosa* in association with graptolites or with other fossils suggesting a Canadian age.

A discussion of the age of the beds exposed in the Chaudière falls section will be postponed until after the description of the other sections.

VILLE GUAY SECTION

This section is well exposed, especially at low tide, on the south shore of the St. Lawrence, about 5 miles east of Lévis. The section was described by the writer (Rasetti, 1945a), but for the understanding of the stratigraphy of the area it is necessary to repeat the description, with additional observations made in 1945.

About 4½ miles east of Lévis, a band of conglomerate forms a conspicuous outcrop on the shore. East of this conglomerate, the strata, which strike almost perpendicular to the shore (N. 32°–35° E., magnetic) are excellently exposed and maintain an almost constant dip of 60°–70° SE. A conformable succession of about 1700 feet of strata can be ascertained, beginning 11 feet below the base of the conglomerate, where the strata are cut off by a fault (Fig. 3).

The succession in descending order is the following:

	Thickness of unit	Thickness to base of section
	Feet	
13. Green shale	90	1669
12. Gray shale, with six or seven layers, 2 to 3 inches thick, of dark-gray, sparsely fossiliferous limestone (*Ellsaspis* zone). Fossils: *Orthis* cf. *panderiana* Hall and Clarke, *Orthis* cf. *billingsi* Ulrich and Cooper, *Ellsaspis elliptica* Rasetti (Pl. 2, fig. 2)	3	1579
11. Green and gray shale	36	1576
10. Alternating beds of red, green, and gray shale	360	1540
9. Gray and green shale	110	1180
8. Alternating layers of shale and heavy-bedded sandstone	140	1070

	Thickness of unit	Thickness to base of section
	Feet	
7. Gray and green shale with thin sandstone beds	240	930
6. Alternating layers of shale and heavy-bedded sandstone	35	690
5. Gray and green shale with thin sandstone beds. Thin limestone layers are present at several horizons; some of them yielded small unidentifiable linguloid brachiopods. On the Island of Orléans, equivalent beds, 200 feet above the base, yielded *Callograptus*	610	655
4. Limestone conglomerate, almost entirely consisting of fragments of various sizes of light- to dark-gray limestone, often sandy. Some of the boulders of darker limestone are abundantly fossiliferous and yield a Lower Cambrian and possibly also an early Middle Cambrian fauna	10	45
3. Gray shale, with thin sandstone beds	12	35
2. Conglomerate, containing mostly light-gray limestone pebbles in a sandstone matrix	12	23
1. Gray, rusty-weathering shale with a few thin, generally lenticular beds of impure, dark-gray, fossiliferous limestone (*Austinvillia* zone). Fossils: *Austinvillia bicensis* Resser, *Bonnia* sp., *Pagetides amplifrons* Rasetti, *Pagetides pustulosus* Rasetti, *Periomma punctata* Rasetti	11+	11

Special attention was devoted to the contact between the shale of the *Austinvillia* zone and the lower conglomerate bed, a contact supposed to represent the Lower Cambrian-Canadian boundary as it will be set forth later. No angular or erosional unconformity could be detected, notwithstanding the great gap in the sedimentation (Pl. 2).

ORLÉANS ISLAND SECTION

The strata exposed on the southern coast of the Island of Orléans, representing Logan's typical section of the "Lévis formation" in the original meaning of the name, are of little value as a whole, as the beds are much too disturbed to permit a clear recognition of their order and thickness. However, a portion of the strata supply extremely valuable information to supplement the observations made on the Ville Guay section.

Looking at the southern coast of the island from the opposite shore at Ville Guay, one notices that the conspicuous conglomerate of the Ville Guay section has several outcrops on Orléans Island, approximately on the projected strike of the beds at Ville Guay. A detailed examination of these outcrops shows that the conglomerate and the associated shales form a series of folds plunging toward the south, and the conglomerate outcrops seven times on the shore. The pebbles in all these outcrops yielded lower Cambrian fossils.

Beginning at the west, about 2 miles from the western end of the island, one meets four of these outcrops in close succession. The structure of these strata can be clearly ascertained, as the conglomerate can be followed inland and constitutes a continuous bed. The structure is represented diagrammatically in Figure 4. The general structure is a syncline, containing, in a smaller scale, two synclines and an anticline. Hence the strata west of the first and east of the fourth outcrop of the conglomerate are older than the conglomerate itself, while those between the first and second outcrops of the conglomerate, and those between the third and fourth, are younger.

If we compare these outcrops with those at Ville Guay, the most conspicuous difference is the presence on Orléans Island of only one instead of two beds of conglomerate

FIGURE 2. Botsfordia pretiosa SHALE EXPOSED NEAR THE CHARNY BRIDGE

FIGURE 1. FALLS OF THE CHAUDIÈRE, SHOWING THE TYPE SECTION OF THE CHARNY FORMATION

EXPOSURES OF THE CHARNY FORMATION ON THE CHAUDIÈRE

FIGURE 2. SHALE AND THIN-BEDDED LIMESTONE OF THE ELLESAPIS ZONE

FIGURE 1. CONTACT BETWEEN THE SHALE OF THE AUSTINVILLIA ZONE AND THE VILLE GUAY CONGLOMERATE

The hammer rests on one of the thin limestone layers containing the *Austinvillia* fauna. This contact is assumed to represent the Lower Cambrian-Canadian boundary.

separated by a narrow shaly interval. This bed varies in thickness between 12 and 24 feet. However, the conglomerate at the two localities undoubtedly has the same stratigraphic position. The beds above the conglomerate on the island are identical with those in the corresponding position in the Ville Guay section. The beds below the conglomerate on the island to not show the thin-bedded limestone containing the

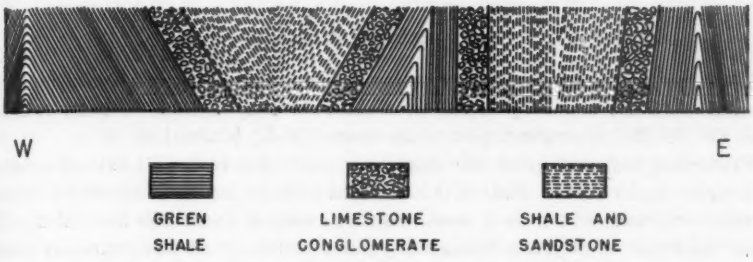

FIGURE 4.—*Diagrammatic structure of a portion of the south shore of the Island of Orléans*

Austinvillia fauna. It is not surprising, in view of the generally lenticular character of the beds in this area, to find that these thin layers do not extend laterally across the river. In place of the shale with limestone lenses of the *Austinvillia* zone, one finds a green, gritty, glauconitic shale, showing poor cleavage and crumbling upon weathering into irregular fragments. A thickness of 420 feet of this shale can be measured west of the westernmost outcrop of the conglomerate; farther west the preceding strata are repeated by folding. Thus the Orléans Island section enables one to add 400 feet of strata below the lowest ones present in the Ville Guay section, where a fault breaks the succession just a few feet below the conglomerate.

The remaining three outcrops of the conglomerate occur about a mile to the east. The strata on either side of the conglomerate are just like those discussed. These exposures are important because thin limestone beds (similar to those occurring in the same position at Ville Guay), 220 feet stratigraphically above the conglomerate (east of the easternmost conglomerate outcrop), yielded well-preserved specimens of a *Callograptus*. This find very conveniently supplements the fossil evidence resulting from the Ville Guay section.

East of the above-discussed localities there are no more outcrops of the conglomerate on the south shore, and all the strata, extremely disturbed, that occupy the shore to the end of the island appear to be above the conglomerate and to correspond to the main portion of the Ville Guay section.

Near the north shore and the eastern end of the island, however, are other outcrops of the conglomerate. The upturned conglomerate bed roughly parallels the road, 3-4 miles east of the village of Ste. Famille, and is displaced in several places by small faults. The beds on which the conglomerate rests (on the north side) are of the same green, glauconitic shale observed in the outcrops on the south shore. An additional observation can be made here—*i.e.*, that the conglomerate includes fragments of the

glauconitic shale—again proving that this shale is older than the conglomerate. Several hundreds of feet of the shale can be seen below the conglomerate. The lower beds gradually change to a more fissile, fine-grained shale that in places is not dissimilar lithologically from the *Botsfordia pretiosa* shale; however, no fossils could be found, hence the assumption that this is approximately the stratigraphic position where the *Botsfordia pretiosa* shale should be expected to occur remains hypothetical.

POINTE MARTINIÈRE SECTION

The exposure is on the south shore of the St. Lawrence at Pointe Martinière, about 3 miles east of Lévis and 1½ miles west of the Ville Guay section. The strike of the beds (N. 30° W.) is perpendicular to the shore; the dip is about 85° W.

Proceeding eastward along the shore, one observes a fault just east of a bed of dolomitic conglomerate. East of this fault the beds are not too disturbed for a considerable distance and show a conformable succession about 800 feet thick. The exact thickness is uncertain because beyond a certain point the strata are closely folded with repetition of the beds. The general structure at this locality is a syncline, since the younger beds occur in the middle. The strata were measured on the western limb of the syncline.

	Thickness of unit	Thickness to base of section
	Feet	
11. Gray and green shale with numerous thin beds of fine-grained, dark-gray, fossiliferous limestone. Fossils: *Ogygites* sp. (very large species), *Ampyx* sp. (several cranidia and pygidia), *"Agnostus" sp.*	42	831
10. Green shale, with some gray and red shale	84	789
9. Harder, tan-weathering gray shale	8	705
8. Green and gray shale, with some thin limestone beds	40	697
7. Hard, tan-weathering gray shale, containing poorly preserved graptolites	15	657
6. Shale with thin limestone beds	18	642
5. Green shale, with some red shale	78	624
4. Shale with thin limestone beds	30	546
3. Lenticular bed of brecciated sandstone	1–2	516
2. Hard, gray, tan-weathering shale partly filled with graptolites. Fossils: *Tetragraptus* cf. *similis* (Hall), *T.* cf. *quadribrachiatus* (Hall), *Didymograptus* cf. *bifidus* (Hall), *Goniograptus* cf. *geometricus* Ruedemann	15	515
1. Green and red shale, with thin beds of harder shale and sandstone, and a few thin limestone beds at the top	500	500

Possibly there is some repetition in the higher beds of the succession.

CAMBRIAN AND CANADIAN FORMATIONS

LOWER CAMBRIAN: THE CHARNY FORMATION

The stratigraphic and paleontologic evidence presented in the detailed description of localities and sections will now be used in an attempt to interpret the general stratigraphy of the area and to establish the formations that must replace the heterogeneous assemblage hitherto known as the "Sillery".

The writer considers it proved that the oldest beds in the area are those represented in the Chaudière falls section, on the following grounds: (1) The brachiopod *Botsfordia pretiosa*, which Ulrich and Cooper (1938) definitely consider as Lower Cambrian, occurs at the top of the Chaudière falls section; (2) In the Ville Guay section we have a record of sedimentation in the area from the late Early Cambrian to well up in the Canadian, since *Callograptus* occurs 1400 feet below the highest beds. Nowhere in this section do we find either the massive sandstones of the Chaudière or the *Botsfordia pretiosa* shale. Therefore it seems safe to conclude that all the beds on the Chaudière are either younger or older than the strata at Ville Guay. Logan considered those on the Chaudière younger and placed the "Sillery" at the top of the "Quebec group". However, we now know that the youngest Canadian strata in the area are represented by the Lévis formation, entirely distinct from the Chaudière beds by its lithology and fossils. Thus above the Ville Guay section there is no place for the 1500+ feet of strata represented on the Chaudière, and we must accept the interpretation that all the Chaudière beds are below the Ville Guay section. Since the latter has at the base Lower Cambrian strata, it follows that the Chaudière falls section contains only Lower Cambrian rocks.

Now there arises the question of a name for this Lower Cambrian formation. These are the beds that Logan originally designated as the "Sillery"; but the name, for the last 50 years, has been applied to rocks that, over most of their area, are of Canadian age; and consequently "Sillery" is definitely associated in the minds of most geologists with Canadian strata. The writer believes that further use of the term "Sillery" would perpetuate the existing confusion. Since by far the best section of the formation is exposed at the falls of the Chaudière near the village of Charny, the writer proposes the new name, Charny formation.

The type section of the Charny shows 1500 feet of the formation, with the top and bottom concealed. The *Botsfordia pretiosa* shale will be considered as a member of the upper Charny, well characterized by lithology and fossils.

In the Ville Guay section we have the 11 feet of the *Austinvillia* zone to be added to the Lower Cambrian. (For the fossil evidence *see* Rasetti, 1945.) In the Orléans Island section the top of the 420 feet of strata exposed below the conglomerate occupies the position of the *Austinvillia* zone; hence these beds must also be considered Lower Cambrian. These strata, at least tentatively, will be assigned to the Charny, of which they will represent the top, since they are conformably overlain by the Canadian. Unfortunately, it has been impossible to find more direct stratigraphic evidence for the relationship between the typical Charny of the Chaudière falls section and these higher beds of the Island of Orléans; hence the extent of the gap between the two cannot be estimated. This the writer believes to be the most serious gap in our knowledge of the early Paleozoic section of the area. It is likely that the missing beds are represented somewhere in the vicinity, but they cannot be identified unless they are seen in contact with the *Botsfordia pretiosa* shale below and with the basal Canadian conglomerate above. Possibly at least part of the gap may be filled by beds exposed near the north shore of Orléans Island.

In conclusion, the known portions of the Charny are represented by 1500 feet of coarse sandstones and mostly red shales on the Chaudière, followed by a gap of un-

known extent, and finally by the 420 feet of green glauconitic shale on the Island of Orléans. At the top of this shale is the *Austinvillia* zone at Ville Guay, yielding *Bonnia*, *Austinvillia bicensis*, *Pagetides*, and other Lower Cambrian fossils.

Only the uppermost portion of the Charny, the *Austinvillia* zone, contains enough diagnostic fossils to permit even an approximate comparison with other Lower Cambrian formations of eastern North America. P. E. Raymond (private communication) informs the writer that "*Austinvillia* occurs with abundance of *Bonnia* in a new zone found three years ago at the base of the Parker about a mile southwest of Parker Cobble, Vermont". The writer collected a species of *Pagetides* from the Parker shale at the Kelly quarry near Swanton Junction. These finds indicate that the *Austinvillia* zone may not be far stratigraphically from the Parker of northwestern Vermont.

If the interpretation of the stratigraphy here suggested is correct, the *Botsfordia pretiosa* shale is older than the *Austinvillia* zone, but its only significant fossil is obviously insufficient for an accurate correlation. Its assumed position with respect to the *Austinvillia* zone and the presence of *Botsfordia* might vaguely suggest an equivalence with the Schodack of New York, one of whose diagnostic fossils is *Botsfordia caelata*.

LOWER ORDOVICIAN: THE VILLE GUAY CONGLOMERATE AND THE LAUZON FORMATION

Because of the strongly disturbed condition of the strata object of this study and their extremely scarce fossil content, it is fortunate that the paleontologic evidence affords the possibility of locating fairly accurately the Lower Cambrian-Canadian boundary. The fossil evidence from the Ville Guay section shows that the shale of the *Austinvillia* zone, immediately below the conglomerate, is Lower Cambrian. On the other hand, on the Island of Orléans, beds 220 feet above the conglomerate hold *Callograptus*, indicating an Upper Cambrian or Canadian age. These beds were searched most carefully for other diagnostic fossils, but besides the graptolite only yielded almost microscopic linguloid brachiopods and larval forms of trilobites. These fossils, although rather well preserved, are unidentifiable. The graptolite is of a type that occurs in Canadian beds (cf. *Callograptus salteri* Hall), but since Ruedemann (1933) showed that similar forms occur, although very rarely, in Upper Cambrian formations, we cannot definitely exclude the possibility that the strata in question are Upper Cambrian. However, since at Ville Guay there is no sudden change in lithology or apparent disconformity within the 1600 feet of strata above the conglomerate, and thus the *Callograptus*-bearing beds grade upward into beds that are almost certainly of Canadian age, the simplest assumption will be that all of this portion of the section is Canadian.

We shall thus tentatively assume that the conglomerate marks the base of the Ordovician. This conglomerate, because of its important stratigraphic position and rich fossil content, deserves a special name. The writer proposes to designate it as the Ville Guay conglomerate. Its thickness is 12–24 feet on the Island of Orléans. At Ville Guay it consists of two beds, respectively 10 and 12 feet thick, separated by 12 feet of shale. The contact between the lower conglomerate and the *Austinvillia* shale (Pl. 2) is taken as the Lower Cambrian-Canadian boundary.

It must be emphasized that this conglomerate, in common with those in the Lévis formation and others, also probably of Canadian age, observed at several places farther east on the south shore of the St. Lawrence, has the peculiar characteristic that the source of the boulders is unknown. Most of them are not derived from the underlying rock, but from massive limestone of Lower Cambrian age now unknown in place. The origin of these conglomerates with exotic blocks has been discussed by several authors (Bailey, Collet, and Field, 1928; Kay, 1942), and the writer is unable to contribute any further observations on this question. The occasional presence in the conglomerate of fragments of the underlying shale was mentioned in describing the outcrops on Orléans Island.

Another term must be employed to designate the Canadian strata forming the main portion of the Ville Guay section—*i.e.*, the 1600 feet above the conglomerate. These strata contain *Callograptus* 220 feet above the conglomerate, and the fossils of the *Ellsaspis* zone 1300 feet higher in the section. The writer proposes that Richardson's term Lauzon be revived as a formation name. In fact, the Lauzon was defined as the supposed upper portion of the strata of Logan's type section on the Island of Orléans (divisions 10 to 17, Logan, 1863, p. 227–228). According to the interpretation here proposed part of these strata belong to the upper Charny (Logan's divisions 10 and 11; thickness was probably overestimated by Logan because he disregarded the repetition of the beds due to folding), but the rest corresponds to the Canadian (or, partly, Upper Cambrian) portion of the Ville Guay section. It must be added that the type section is now situated only 3 miles from Lauzon, hence the name is geographically appropriate. Thus the Lauzon is defined as the strata above the Ville Guay conglomerate and below the Lévis formation.

The Lauzon, as here defined, occupies by far the larger area of the earlier "Sillery" since it is assumed to extend along almost the entire coast east of Lévis for about 270 miles. It consists mainly of green and red shales, with interstratified sandstone and rare limestone beds. Its age seems to be mainly Canadian, but the lower portion may be Upper Cambrian.

There now arises the question of the upper limit of the Lauzon. In the section at Pointe Martinière red and green shales, of typical Lauzon lithology, grade into green, magnesian shales containing a typical Lévis *Tetragraptus-Didymograptus* fauna. The associated limestones yield the trilobites *Ampyx* and *Ogygites*, besides an agnostid of an Ordovician type. All these fossils suggest a rather late Canadian age (the trilobites alone might as well indicate a Middle Ordovician age). Hence there can be no sharp limit between Lauzon and Lévis. Nevertheless, the Lévis deserves recognition as a separate formation because of its characteristic lithology (green, magnesian shales alternating with black graptolite-bearing shales, peculiar beds of fossiliferous limestone conglomerate, thin-bedded *Shumardia* limestone, etc.). The writer's impression is that the typical Lévis is a deposit of very limited areal extent, and possibly equivalent beds in the eastern portion of the area considered in this paper show the poorly fossiliferous Lauzon lithology. It is likely that the Pointe Martinière section partly overlaps the Ville Guay section, but it almost certainly extends into higher beds, the highest of which must be considered as Lévis. Thus we may roughly evaluate the thickness of the Lauzon in the Lévis area at 2000 feet, with a

rather indefinite upper limit with the overlying Lévis. At other localities farther east the Lauzon is probably considerably thicker.

EXTENSION OF THE FORMATIONS IN THE EASTERN AREA

The application of stratigraphic results derived from the study of the Lévis-Chaudière area to the remaining outcrop area of the former "Sillery" does not present an easy problem, since the Lower Cambrian and Canadian strata are lithologically similar; both consist mostly of green and red shales. Hence only paleontologic evidence can be relied upon to decide whether the strata should be assigned to the Charny or to the Lauzon.

The easternmost occurrence of *Botsfordia pretiosa* known to the writer (as already pointed out, all references in the earlier literature are unreliable) is 3 miles east of St. Vallier, 20 miles northeast of Lévis. Hence outcrops of the Charny extend at least that far eastward. However, it is the writer's impression that most of the strata east of this locality are to be referred to the Lauzon. This is true in particular of the massive quartzites that begin to appear along the coast in the vicinity of Ste. Anne de la Pocatière and extend for about 30 miles eastward, forming conspicuous hills because of their great resistance to weathering. This quartzite represents a new facies, unknown in the Lévis-Chaudière area. Dresser (1912) believed that the quartzite underlies the "Sillery" shale unconformably and considered it the oldest rock in the area. He designated it as the Kamouraska quartzite. Other authors, however (McGerrigle, 1934; De la Rüe, 1941), have probably been right in concluding that the quartzite forms lenticular masses interstratified with the shale. Indirect fossil evidence shows that the quartzite can hardly be older than Canadian. Beds of limestone conglomerate are often interstratified with the quartzite. Raymond (*in* Dresser, 1912) had already shown that the conglomerate associated with the typical outcrop of the quartzite described by Dresser yields Upper Cambrian fossils. The writer (Rasetti, 1945b) collected numerous fossils from the pebbles at Dresser's locality and established that they belong to the *Hungaia magnifica* fauna, well known from the boulders at Lévis. This fauna is of late Trempealeau age (Rasetti, 1944). Hence the quartzite cannot be older than late Trempealeau, and almost certainly is Canadian. We shall consider it as a local facies of the Lauzon.

A section of the "Sillery" at Rivière du Loup was described by Young (1913). Raymond (*in* Young, 1913) studied a few fossils collected at this locality and concluded the strata were Lower Ordovician. Hence we may assign these rocks to the Lauzon, of which they are typical lithologically.

Farther east, massive beds of quartzite interstratified with sandstone and limestone conglomerate occupy part of the coast between Trois Pistoles and Bic. At Bic the conglomerates attain a great development and have been well known since Weston discovered Lower Cambrian fossils in the boulders. The conglomerates and quartzites alternate conformably with red and green shale of typical Lauzon aspect. As far as the writer knows there is no fossil evidence for the Canadian age of these shales, quartzites, and conglomerates, but they probably represent the equivalent of those exposed in Kamouraska County; hence they may be also tentatively assigned to the Lauzon.

East of Bic the conglomerates and quartzites appear in the vicinity of Métis. Near the outlet of the Little Métis River, the conglomerate is in contact with a black shale, which has received the special name of Métis shale (Howell, 1944) because of its important fossil content. Howell considers this shale to be probably of early Canadian age. The pebbles in the associated conglomerate yield Lower, Middle, and lower Upper Cambrian (Dresbach) fossils, thus indicating that the conglomerate cannot be older than Upper Cambrian. Hence it appears justified to consider the Métis shale as a local member of the Lauzon. Less than 3 miles east of the outcrop of the Métis shale, about 300 feet east of the church at Les Boules, the writer collected abundant specimens of *Dictyonema* cf. *flabelliforme* in thin limestone beds on the shore. This fossil is indicative of an early Canadian age; but unfortunately the beds in this area are so contorted and broken that it is impossible to ascertain the relative position of the Métis shale and of the *Dictyonema* beds.

Twenty-five miles farther east, near the outlet of the Matane River, black shales are filled with the same *Dictyonema* (Lapworth, 1887; Ells, 1892). There seems to be little doubt that all the red, green, and black shales that occupy the coast in the vicinity of Matane are of Canadian age; hence these beds, like the preceding, may be assigned to the Lauzon.

The easternmost outcrops of quartzite and limestone conglomerate occur between Grosses Roches and Méchins, about 20 miles east of Matane. Here we have no fossil evidence from the shale, but pebbles in the conglomerate yield an abundance of Dresbach fossils, indicating that the beds are not older than Upper Cambrian. These conglomerates are identical in fossil content and lithology with those at Métis, and they probably occupy the same stratigraphic position.

East of Méchins, findings of upper Canadian and Middle Ordovician graptolites, already cited, indicate that most of the coast is occupied by younger rocks, which do not concern us here.

In conclusion, a brief examination of the rocks outcropping along 270 miles of coast east of Lévis shows evidence for a Canadian age of the strata at several places, and no evidence for Lower Cambrian formations, excepting localities near Lévis. This appears to justify the statement that the "Sillery" is Lower Ordovician (*i.e.*, with the present terminology, Lauzon) over most of its outcrop area.

CONCLUSIONS

The interpretation of the stratigraphy of the Lévis-Chaudière area here proposed may be summarized as follows. The oldest series, whose base has nowhere been observed, consists of coarse sandstones alternating with red shales, and of green shales in the upper part. Its total thickness considerably exceeds 2000 feet. This series of strata, named the Charny formation, is assigned to the Lower Cambrian, since fossils of this age appear in its upper portion. A continuous section of the formation could not be found; the lower 1500 feet are represented in the Chaudière falls section, the uppermost 420 feet on the Island of Orléans, with an undetermined gap between.

This series is succeeded by a long interval of nondeposition, covering the entire Middle Cambrian and probably all or most of the Upper Cambrian. No evidence of diastrophism and consequent erosion corresponding to this period of nonsedimenta-

tion could be observed; the Ville Guay conglomerate apparently overlies conformably the top of the Lower Cambrian wherever the contact is observed. This conglomerate is supposed to represent the base of the Ordovician, although the evidence is not sufficient to prove that it was not deposited in Late Cambrian time. There follows a thick series of red and green shales with interbedded sandstones; the shales are similar lithologically to those deposited in the early Cambrian. At least in the Lévis-Chaudière area, these strata can sometimes be distinguished from the Charny by the more frequent presence of calcareous or dolomitic beds, which are excessively rare in the Charny. For the lower portion of these beds, probably exceeding 2000 feet in thickness, the old formational name of Lauzon is proposed. The Lauzon grades upward into the upper Canadian Lévis formation, whose stratigraphy and thickness are poorly known (Clark, 1924; 1926) on account of the extremely disturbed condition of the beds.

East of the Lévis-Chaudière area, the south shore of the St. Lawrence is occupied for about 270 miles by shales with interbedded quartzites, sandstones, and limestone conglomerates. Evidence is presented to show that, at least at many places, these strata are of Canadian age and hence can be referred to the Lauzon formation.

The writer realizes that the interpretation of the stratigraphy here proposed is sharply at variance with the ideas that have prevailed during the last 50 years and which essentially date from Ells' work. The current idea was that the "Sillery" represented a single series of beds, either entirely Canadian, or at most Upper Cambrian in its lower portion. However, the writer believes that the evidence of the fossils leads to the conclusion here proposed; in particular, the occurrence of the Lower Cambrian trilobites of the *Austinvillia* zone just below the Ville Guay conglomerate, and of *Callograptus* 220 feet above, leaves no doubt that we have to do with two entirely distinct series of strata.

To make the proposed solution more readily acceptable to geologists, the writer wishes to recall the analogy between the Lévis-Chaudière area and the "slate belt" of Washington County, New York, and of the adjacent portion of Vermont—an analogy which extends to structure, stratigraphy, and lithology. In Washington County, as in the area here discussed, the Taconic thrust sheet consists mostly of shales not dissimilar lithologically from those that constitute the "Sillery". Walcott's work (Dale, 1899) showed that these shales, the "Taconic" shales of Emmons, really represent two distinct series: the Lower Cambrian Schodack formation and the early Canadian Schaghticoke shale. The two are so closely folded together and so similar lithologically that only the fossil evidence suggested the presence of strata of two widely different ages and enabled Walcott to effect the separation. The problem was easier and hence could be solved much earlier because fossils of the formations in Washington County are far more abundant than in the rocks here discussed.

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GEOLOGY AS A PROFESSION

The Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., now has for distribution, at a price of 10 cents, an excellent small booklet entitled *Geology as a profession*, Vocational Booklet No. 1, which is prepared by the National Roster of Scientific and Specialized Personnel. The author is Miss Ann R. Taylor, working under the direction of Dr. W. T. Read, Chief of the Research Section, with the advice and assistance of many geologists. This booklet describes in about 20 pages the profession of geologists (not including geophysicists). It gives the subdivisions of the geological profession, the working conditions and types of employment, the opportunities for women, the related fields of employment, beginning jobs, advancement and conditions of employment, post-war outlook in the profession, and the qualifications and training, and makes suggestions as to how to get a start. It is attractively illustrated. It would be of special value to advisers of young students and, while written primarily from the employment point of view, would also give those entering the profession a condensed and businesslike summary of what they might expect.

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Funds have been made available to The Arctic Institute of North America by which it is possible to offer two Fellowships of up to $2000 each (Canadian currency) for scientific work in the Canadian Arctic or Subarctic during 1947.

The Fellowships are open to anyone who has demonstrated his ability to carry out research work of superior quality in some field of science.

Applications must be received by November 1, 1946. Fellowships will be awarded on the recommendation of the Board of Governors of the Arctic Institute and will be announced by February, 1947.

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CIVIL SERVICE ANNOUNCES GEOLOGIST EXAMINATION

Geologists now have the opportunity to compete for probational appointments leading to permanent status in the Federal service, the Civil Service Commission has announced. Persons appointed from the examination will serve in essential positions in such agencies as the Geological Survey of the Department of the Interior and the Bureau of Plant Industry and the Soil Conservation Service of the Department of Agriculture. Most of the positions are located in Washington, D. C., and throughout the United States, but some appointments may be made to positions in the territories and possessions of the United States and in foreign countries.

The entrance salaries for Geologists appointed from this examination are $2,644 and $3,397 per annum. Their work will include such activities as making and recording geological observations; identifying and studying specimens of rock, fossils and ores; and carrying on or assisting in geological mapping.

The age limits for this examination, except for persons entitled to veteran preference, are 18 to 62 years. A written test is required of all applicants. In addition to passing the written test, applicants for the P-1 ($2,644) grade must have successfully completed a full 4-year course of study leading to a bachelor's degree, with at least 30 semester hours' study in geology; *or* they must have had 30 semester hours in geology plus appropriate experience to equal a 4-year college course. Persons applying for the P-2 ($3,397) grade must meet the requirements for the P-1 grade, and in addition must have had two years of professional experience in the field of geology. Further details are contained in the examination announcement.

Announcements and application forms may be obtained from first- or second-class post offices, from any of the Civil Service regional offices, or from the central office of the Civil Service Commission in Washington, D. C.

Applications must be received in the Commission not later than August 7, 1946.